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Handbook: Manufacturing Advanced Composite Components for Airframes

April 1997

Final Report

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16. Abstract

This handbook is a compendium of information on methods of manufacture of advanced composite components for airframes. It is aimed at familiarizing the reader with the common industry standards and aspects of using composites in aircraft applications. The handbook is intended to aid Federal Aviation Administration (FAA) personnel in assessing airworthiness of composite parts in civilian aircraft. The contents are drawn from various sources and are condensed into an easy-to-read, but comprehensive format.

The contents of this handbook include introductory background on composite materials utilizing fiber reinforcements, matrix systems, core types and styles, handling, related practices found in the manufacturing and fabrication as well as the use of these materials, the concepts of producing parts utilizing tooling, various manufacturing methodologies, processing, machining, quality assurance, assembly, repair, and related safety and environmental issues.

These topics are considered essential for proper assessment of the manufacturing qualities and the continued airworthiness of composite parts used in civil aviation today and in the future.

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FOREWORD

The intention of this handbook is to provide basic information on principles, fundamentals, and technical procedures related to the manufacture, inspection, and repair of fiber-reinforced composites used in civil airframes.

The subject matter is treated from a generalized point of view and should be supplemented by reference to the manufacturer's instructions. Since the handbook is primarily to be viewed as a instructional and reference tool, the methods, techniques, and practices contained herein are not to be construed as official Federal Aviation Administration (FAA) position.

This handbook is published as a version and an update to the previously published Handbook: An Engineering Compendium on the Manufacture and Repair of Fiber-Reinforced Composites, DOT/FAA/CT-87/9. Some material that was more engineering oriented in that handbook has not been retained in this revision and therefore the original handbook should not be discarded.

The user of the handbook should also be aware of sister FAA publications DOT/FAA/CT-85/6, Vol. I, Composite Materials and Laminates, and its revision DOT/FAA/AR-95/29, Fiber Composite Analysis and Design Textbook, Vol. 1, and DOT/FAA/CT-88/18, Fiber Composite Analysis and Design, Vol. II, Structures.

Advancements in composite manufacturing, inspection, and repair technology require that an instructional/training handbook be under continuous review and updated periodically for it to be useful. Therefore, the FAA would appreciate receiving suggestions for improving the content and relevance of this handbook. Pertinent correspondence should be addressed to:

Federal Aviation Administration
William J. Hughes Technical Center
Structural Airworthiness Branch, AAR-431
Atlantic City International Airport, NJ 08405

PREFACE

This handbook was developed under FAA Grant No. 95-G-045 administered by the Department of Transportation, FAA William J. Hughes Technical Center, Atlantic City International Airport, New Jersey 08405. Randy W. Peebles was the Project Manager with Terry L. Price as the Principal Investigator. The FAA technical manager for this project was Peter Shyprykevich with the guidance of Joe Soderquist, the FAA National Resource Specialist, Composite Materials.

The following Cerritos College personnel developed, designed, and wrote the handbook:

Terry L. Price, Principal Investigator-Technical Coordinator

George Dalley, Technical Advisor/Writer/Editor

Patrick C. McCulloch, Technical Advisor/Writer/Editor

Lee Choquette, Technical Advisor/Writer/Editor/Graphic Coordinator

Graphics design and support for the handbook was provided by Teri Tsosie and Chris Sparger. Linda D. Clegg provided assistance with technical editing, and secretarial support was provided by Ruby Miller, Emily Fahey, Gayle Kline, and Melody Seewoster.

Technical Assistance was provided by the FAA William J. Hughes Technical Center, Boeing Aircraft Company customer service department, Northrop Grumman Corporation, Thermal Equipment Corporation, Airtech International, McDonnell Douglas Corporation, United Airlines Maintenance Operations, Society of Automotive Engineers (SAE), Commercial Airlines Composite Repair committee (CACRC), and from MIL-HDBK-17 and MIL-STD-453. Special thanks to the following individuals for their technical assistance in preparing this handbook; Sam Dastin, Rick Barrett, George Eqstein, and William Heimerdinger.

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EXECUTIVE SUMMARY

This handbook is a compendium of information on methods of manufacture of advanced composite components for airframes. It is aimed at familiarizing the reader with the common industry standards and aspects of using composites in aircraft applications. The handbook is intended to aid Federal Aviation Administration (FAA) personnel in assessing airworthiness of composite parts in civilian aircraft. The contents are drawn from various sources and are condensed into an easy-to-read, but comprehensive format.

The contents of this handbook include introductory background on composite materials utilizing fiber reinforcements, matrix systems, core types and styles, handling, related practices found in the manufacturing and fabrication as well as the use of these materials, the concepts of producing parts utilizing tooling, various manufacturing methodologies, processing, machining, quality assurance, assembly, repair, and related safety and environmental issues.

These topics are considered essential for proper assessment of the manufacturing qualities and the continued airworthiness of composite parts used in civil aviation today and in the future.

1. INTRODUCTION.

1.1 BACKGROUND.

The basic concept of composite materials came into being because there has never been a single homogeneous material which has been superior in all the desirable attributes which dictate the selection of materials for specific applications. A material's ultimate potential will always be limited by the fundamental inability to modify some key physical property. So for centuries, man has been combining two or more essentially nonhomogeneous materials, each exhibiting unique structural benefits into a single nonhomogeneous material which will have the best characteristics of both materials. The Egyptians combined mud and straw to produce a superior brick, the combination of iron and steel for greater strength lead to Damascus gun barrels and Samurai swords, and today bridges and walls are constructed by combining steel and concrete. Hence the term composite, "A material containing two or more distinctive materials designed to develop specific performance properties."

Fibrous composites entered the scene as plastic resins were developed and mixed with fiberglass. The late forties saw the first common usages in the recreational industry: fiberglass-reinforced polyester resins for boats and fiberglass-reinforced phenolic-nylon for fishing poles. Fiber-reinforced plastics (FRP) are a subdivision of the composite field in which the matrix (resin) is a polymer (or plastic) and the reinforcement is always a fiber. This is the largest subdivision of composites. Common usage has now largely assigned the terms FRP or fiber-reinforced plastics to the more narrow field of fiberglass reinforcement of polyester resins.

Composites began to find limited application in aircraft but due to the relatively low stiffness and strength of fiberglass and available resins they were restricted to nonstructural applications such as fairings. In the sixties, companies began to investigate newly emerging high-strength fiber-resin systems as potential structural materials. This new breed of composite materials, unlike metal both in properties and method of fabrication, came to be known as advanced composites.

The term advanced composites designates certain composite materials with superior properties. Although the term is not precise, it generally refers to composites with greater than 50% fibers by volume and with a modulus of elasticity of the reinforcement (fiber) greater than 30×10^6 psi. According to common usage, composites are divided into two classifications: FRP and advanced composites.

1.2 SCOPE OF THIS HANDBOOK.

The contents of this handbook will address the manufacturing, inspection, and repair of load bearing composites in civil aircraft. The organization and flow of this handbook are arranged to mirror that of the conventional processing of a composite part (figure 1).

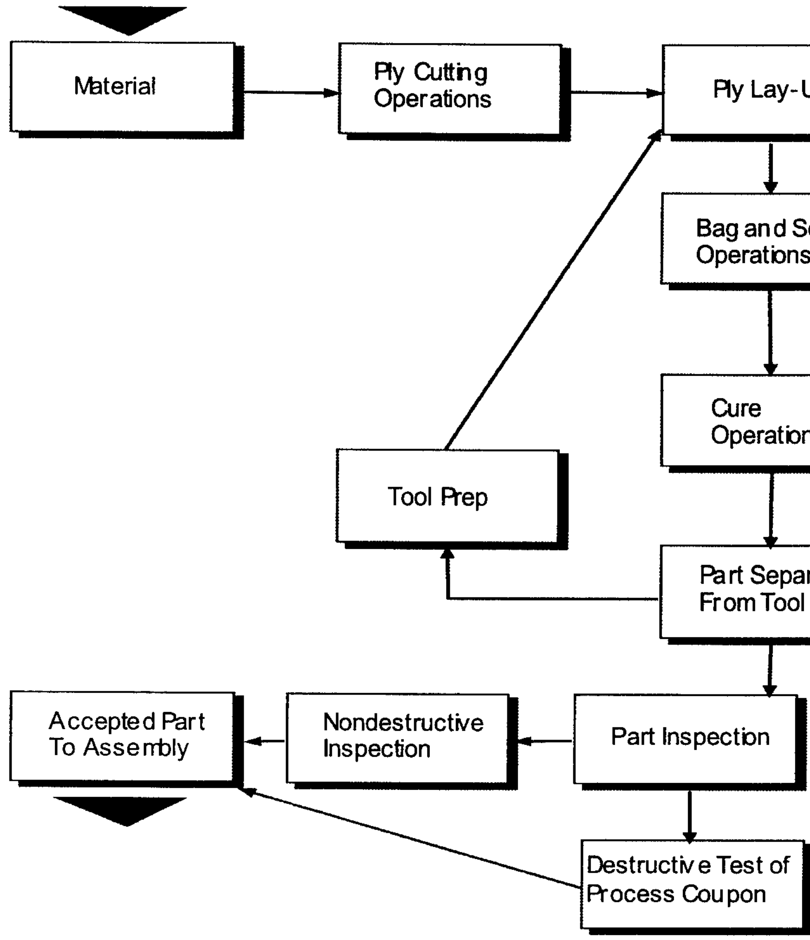


FIGURE 1. MANUFACTURING FLOW CHART

First, as with any material, an understanding of the basic materials with details on their unique properties are covered. Next, steps required in the fabrication of a composite, beginning with the lay-up and orientation of the material in the mold, are described. From there, bagging, processing (cure), trimming, and installation of the composite parts are covered. Other topics include inspection, damage identification, repair, and safe handling requirements. The intent of this handbook is to assist Federal Aviation Administration (FAA) personnel in their training and understanding of composites. Therefore, information contained herein is not to be regarded as authority over maintenance manuals or other official documents.

1.3 TERMINOLOGY.

As with any new endeavor an understanding of the terminology is most helpful if not mandatory. The various branches of the composite industry have given birth to terms that are unique to this specialty field. A glossary of terms that are unique to composites and others that are frequently used in this field are covered in Section 13, Glossary. The reader is urged to take a few moments before proceeding further to become familiar with these terms.

1.4 RECOMMENDED SOURCES OF INFORMATION.

Section 12 contains a list of references that complements the material presented in this handbook and offers the interested reader additional sources of information. This list includes text books, handbooks, military standards, design guides, journals, and other relevant publications.

Especially recommended are the latest versions of MIL-HDBK-17 Polymer Matrix Composites consisting of three volumes, Vol. I Guidelines, Vol. II Material Properties, and Vol. III Utilization of Data. These documents are available from

Naval Publications and Forms Center
Standardization Documents Order Desk
Bldg. 4D
700 Robbins Avenue
Philadelphia, PA 19111-5094

2. MATERIALS.

2.1 INTRODUCTION.

The discussion in this section is limited to advanced composites primarily used in civilian aircraft. Advanced composites is a family of high-performance materials obtained by reinforcing a matrix material with fibers characterized by high-strength and stiffness properties. The fiber and matrix selection is a science in itself. Proper material selection is based on a multitude of factors, some of which include performance criteria of the part and manufacturing cost.

Generally, fibers made from aramid, boron, or carbon/graphite are utilized for critical applications where strength and weight are key parameters in the part design. Where part performance is less critical and economics is the driving force behind material selection, fiberglass may be the material of choice. A comparison of tensile strength and stiffness of metals and epoxy composites is shown in figure 2.

The selection of a composite material for any application involves the selection of the two constituents—the fiber and the matrix and their fractional volumes in the composite form.

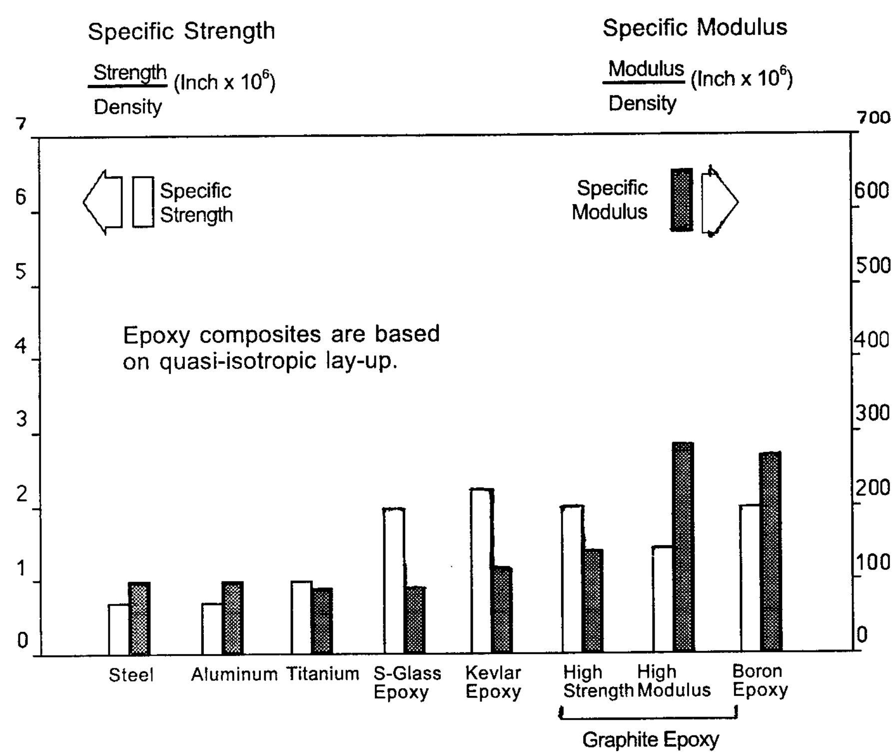


FIGURE 2. PROPERTY COMPARISON OF METALS AND EPOXY COMPOSITES (60% FIBER VOLUME)

2.2 FIBER FORMS.

Many classes of reinforced fibers are currently available. The fibers that have been used in aircraft components include glass, aramid, carbon (graphite), and boron. Reinforced fibers such as ceramic, metallic, and whiskers are still in an embryonic stage and will not be addressed here. Reinforced materials, usually fibrous, that are blended into a matrix or resin binder give the composite a mechanical ability to carry loads greater than either the base resin or the matrix material individually. The two basic types of reinforced placements are dry and wet. Dry reinforcements have no resin while wet fibrous materials are impregnated with a resin (i.e., prepregs).

Fibers are used in many different forms. The most common commercial forms of fibers are strands (which can be used as is or chopped), fabric, or tape. The method to be used in the fabrication of the composite often determines the shape of the reinforcement. The different types of reinforcements are as follows:

- Band—The thickness or width of several rovings or tows as it is applied to a mandrel or tool.
- End—Referring to the termination of a group of filaments in long parallel lengths.
- Fiber—A general term for a material that has a long axis which is many times greater than its radius.
- Filaments—The smallest unit of fibrous material. This is the unit formed by a single-hole in the spinning process.
- Strand—Usually refers to a bundle or group of untwisted filaments but has also been used interchangeably with fiber and filament.
- Tow—An untwisted bundle of continuous filaments, usually with a specific filament count.
- Roving—A number of yarns or tows collected into a parallel bundle without twisting.
- Tape—A collection of parallel filaments (often made from tow) in which the filaments are held together by a binder which usually consists of the composite matrix/resin. The length of the tape, in the direction of the fibers, is much greater than the width, and the width is much greater than the thickness.

- Yarn—A twisted bundle of continuous filaments, hence a twisted tow. A yarn is often used for weaving.
- Woven Fabric—A planar material made by interlacing yarns or tows in various specific patterns.

Figure 3 is a simplified illustration of comparisons between glass, Kevlar, and carbon fibers, specifically the relationship in size and fiber terminology with its corresponding reinforcement family and classification.

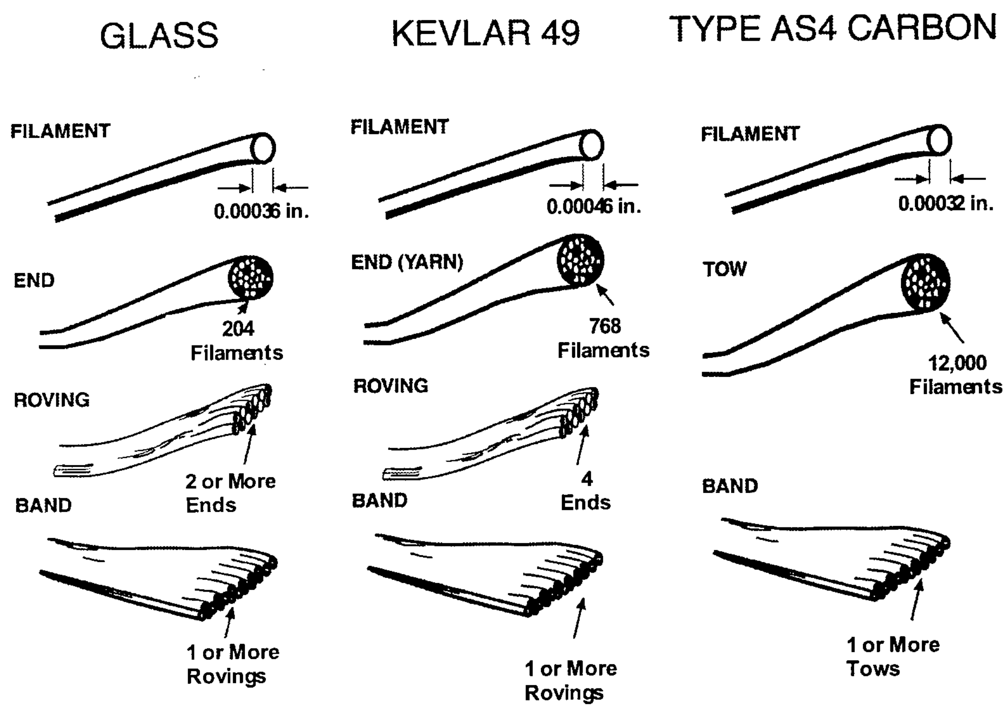


FIGURE 3. FIBER COMPARISON

2.2.1 Prepreg—Unidirectional Tape and Fabric.

Unidirectional tape, or fabric as the name implies, is composed of material having the filaments laid in a single direction, figure 4. It is usually sold preimpregnated with resin to provide stability. Tape is also available in preplied form (more than one layer). Mechanical properties of a composite transverse to the fiber direction depend largely upon the matrix (resin) material and are one order of magnitude lower than the longitudinal properties. Consequently, in the design of most structures subjected to both longitudinal and transverse loadings, the fibers must be orientated in specific directions to withstand these loads. Fabric on the other hand already has fibers running in both directions.

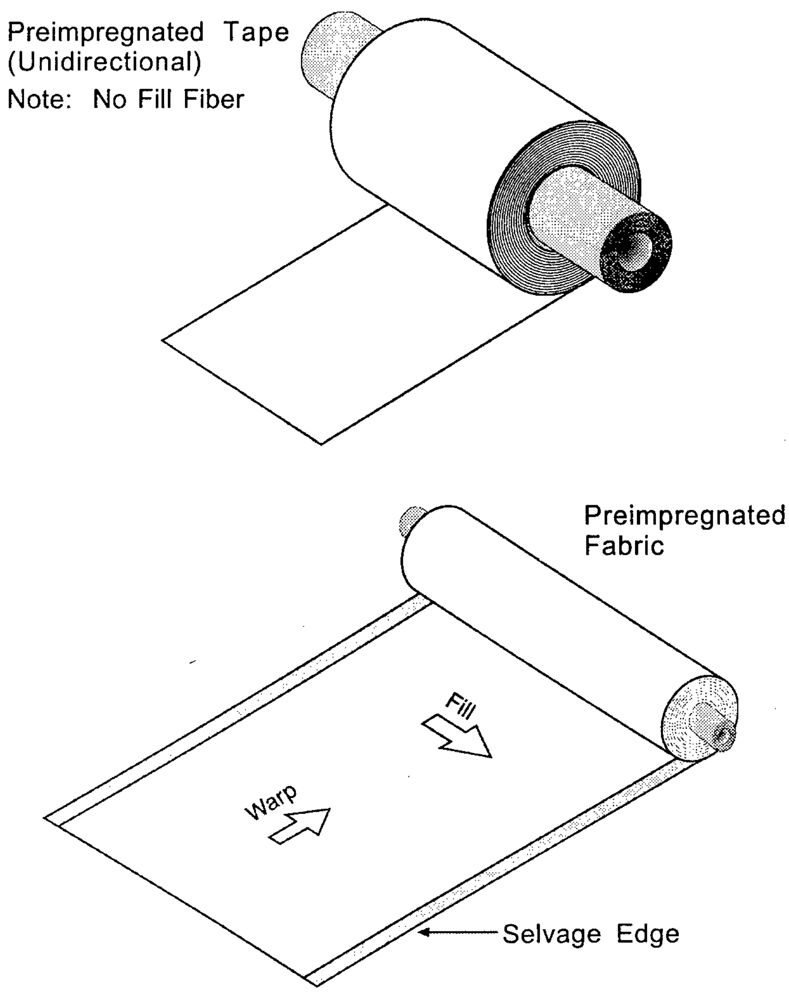


FIGURE 4. PREIMPREGNATED TAPE AND FABRIC

2.2.2 Woven Fabrics.

A fabric is a material constructed of interlaced yarns, fibers, or filaments usually in a planar structure. Typical glass-fiber fabrics are manufactured by interlacing warp (lengthwise) and fill (crosswise) yarns on conventional weaving looms. Such fabrics are woven into a variety of styles with exact control over thickness, weight, and strength. The principal factors which define a given fabric style are fabric count, warp and fill yarn, and weave.

The fabric count refers to the number of warp yarns (ends) per inch and the number of filling yarns (picks) per inch. The weave of fabric refers to how warp and fill yarns are interlaced. Weave determines the appearance and some of the handling characteristics of a fabric. Among the most popular weave patterns are plain, twill, crowfoot satin, leno, and unidirectional. Woven fabrics combine warp yarns along the major axis and fill yarns across the fabric. Unidirectional fabrics have only nominal fibers in the fill direction. Specific properties are controlled by varying the number of filament ends per inch and the type of yarn.

Properties of woven fabrics are also affected by the type of weave used. Some of them are illustrated in figure 5. In the plain weave, one warp yarn alternates over and under one fill yarn. This weave is usually stiffer, more open, and lower in cost. The crowfoot weave, over three and under one, offers better drape than the plain weave for conforming to contours. Satin weaves are smoother and more dense but also take additional effort to remove bubbles in wet lay-ups.

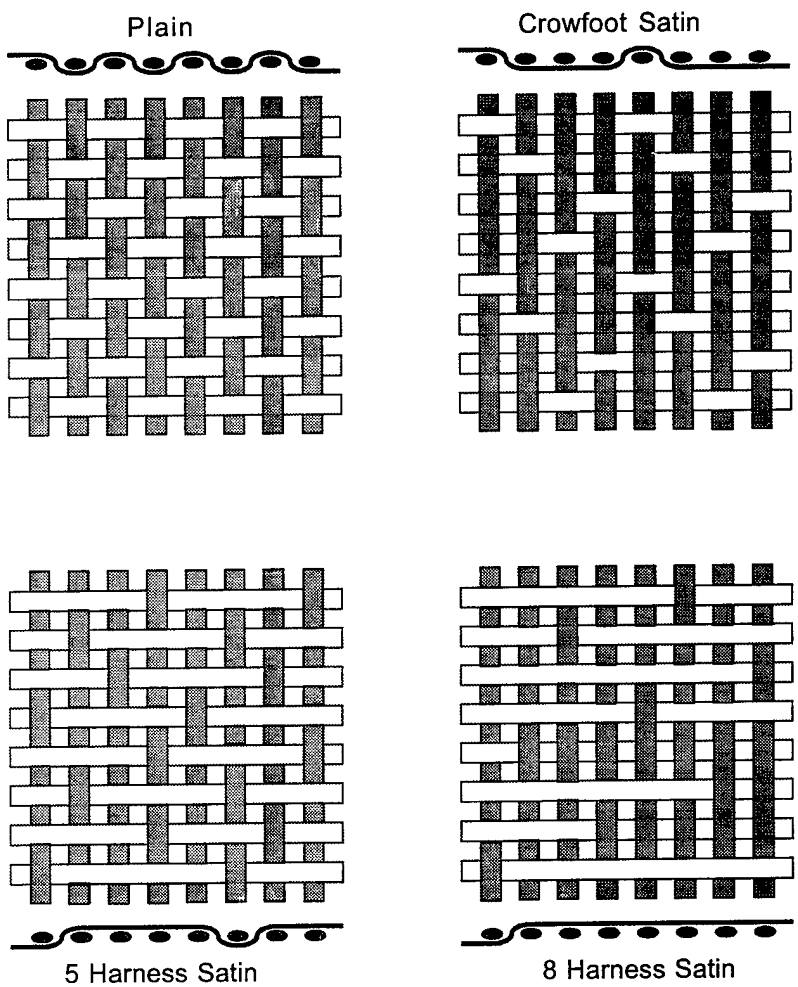


FIGURE 5. FABRIC WEAVES

Although woven fabrics are more expensive than unidirectional tapes, significant cost savings are often realized in the molding operation because labor requirements are reduced. Complex part shapes or processes requiring careful positioning of the reinforcement can benefit from the use of the more workable woven form of fiber.

There are five basic design variables to consider when choosing fabric for industrial use as listed here.

- Thickness—Fabrics are available in thicknesses ranging from 0.0001 to 0.060 in.

- Weight—The weight range begins at less than 1 ounce per square yard and extends to nearly 52 ounces per square yard.

- Construction—This is determined by the number of warp yarns (in the machine direction) and filling yarns (crossmachine direction) per inch of the fabric.

- Yarn Size—Yarn size determines the weight and thickness of the fabric.

- Finish—Most applications require that fabric be used along with another material. For compatibility with other materials, a finish or after treatment is often applied to the fabric.

2.2.3 Reinforcing Mat.

Mat is normally made of relatively short fibers and is used in lightly loaded components. Glass-fiber mat is a blanket of chopped strand or continuous strands laid down as a continuous thin flat sheet. The strands are evenly distributed in a random pattern and are held together by adhesive, resinous binders, or mechanically bound by needling.

The reinforcing ability of continuous-strand and chopped-strand mat is essentially the same, but they have different handling and molding characteristics. Continuous-strand mat can be molded to more complicated shapes without tearing. Needling mat, which has some fibers vertically oriented, is softer and more easily draped than non-needled mat and therefore generally used only where reinforcement conformability is a particular requirement.

2.2.4 Roving.

Roving refers to a group of essentially parallel strands or ends of glass or carbon fibers which have been gathered into a bobbin and typically wound onto a cylindrical tube. Continuous-strand roving consists of parallel-wound strands available in a variety of ends or yields.

Rovings can be woven into a product called woven roving, similar to the way yarns are woven into fabrics. Woven rovings are heavier and thicker than fabrics since rovings are heavier than yarns. They are usually provided in a plain weave although special weaves have been developed. Woven rovings are usually molded by hand lay-up. Typical applications include cargo containers.

Knitting, or stitch bonding, is a relatively new method for producing reinforcing fabrics. Multiple layers of unidirectional reinforcements are stacked and stitched together. Since each layer can be oriented in a different direction, the construction can be tailored to the specific need. These fabrics generally offer better drape and strength than woven fabrics of the same weight, allowing a wide range of options for the designer.

2.2.5 Three-Dimensional Forms.

Three-dimensional configurations refer to a multidirectional oriented reinforcement, allowing anisotropic mechanical properties from X, Y, and Z directions. Fibers can be woven into 3-D preforms. Woven, braided, stitched, or a combination of all these are used to achieve predictable properties for specific aerospace applications. These materials are designed to be used in conjunction with semiautomated equipment to reduce costs while increasing quality by eliminating the human error potential associated with hand lay-up assembly. Semiautomatic weaving processes utilize computer-controlled 3-D weaving machines producing braiding and fiber preforms for closed molded operations. One of the many possible geometries is illustrated in figure 6.

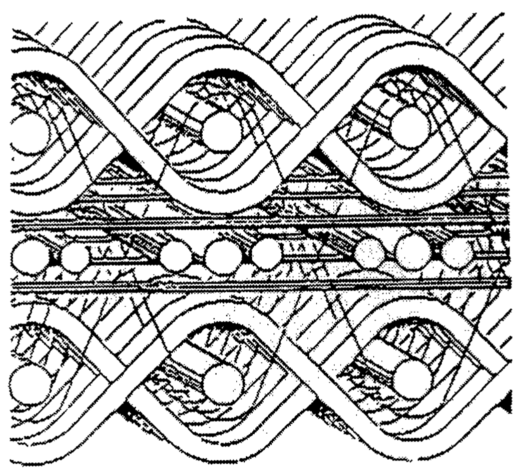


FIGURE 6. GEOMETRY OF ANGLE-INTERLOCK FABRIC (3-D PREFORM)

There are few limits on the composition of reinforcement fibers that can be woven into 3-D preforms. Applicable fibers include carbon/graphite, glass, silica, alumina, aluminosilicates, silicon carbide, cotton, and aramid. Combinations of two or more of these fibers can also be woven in combination if design requirements warrant.

With more than twenty varieties of multidirectional reinforced preforms, 3-D preforms are most widely used. Cylinders, cones, and convergent/divergent sections are commonly designed as preforms utilizing a two-step process. First, a preform of appropriate geometry is woven, then the preform is placed in a metal die, deformed into the required shape, and impregnated with a suitable resinous material to ensure geometric stability during the remainder of the densification process. Their application offers manufacturers multilaminate design requiring only one process for near-net configurations.

Braiding has opened up new opportunities in the near-net shape manufacturing of structural composites. Braided preforms are known for their simplicity, versatility, high level of conformablility, torsional stability, and damage resistance. Braiding has many similarities to filament winding, where dry or prepreg yarns, tapes, or tow can be braided over a rotating and removable form or mandrel in a controlled manner to assume various shapes. The current trend is to expand to large-diameter braiding, develop more sophisticated techniques for braiding over complex-shaped mandrels, multidirectional braiding over near-net shapes, and the extensive use of computer-aided design and computer-aided manufacturing (CAD/CAM).

2.3 FIBER MATERIALS.

Fiber materials that are specifically for use in the composites industry are classified as advanced composite materials. Each exhibits distinct material properties in varying grades for specific applications. Their type, classification, size, and mechanical properties can be optimized when used in conjunction with a resin matrix that effectively carries and transfers the load from one fiber to another. Fiber science is the study of reinforcements and structural fibers for design optimization in various composites manufacturing applications.

2.3.1 Fiberglass (Glass Fiber).

Glass fiber is, by far, the largest volume reinforcement measured by quantity consumed or by sales. Fiberglass accounts for almost 90% of the reinforcements in thermosetting resin configurations. Forms of glass fiber are roving (continuous strand), chopped strand, woven fabrics, continuous-strand mat, and chopped-strand mat. Based on alumina-lime borosilicate composition, E-glass fibers are considered the predominate reinforcement for polymer matrix composites because of their high electrical insulating properties, low susceptibility to moisture, and high mechanical properties. Other commercial compositions include S- and R-glasses with higher strength, heat resistance, and modulus as well as some specialized glass fibers with improved chemical resistance.

Glass fibers are created by mixing various ingredients to a specific formula, melting the mixture in a furnace, and drawing molten glass in the form of filaments, (see figure 7). The specific formula of ingredients is dependent on the end use of the material as exemplified by the unique characteristics of E- glass (electrical applications) and S- and R-glass (strength applications).

The long fibers provide the strength in the composite and continuous fibers provide the most strength. These are all produced in E-glass, S-glass, and D-glass reinforcement grades. The S-glass fiber is the higher strength form and is commonly used in aerospace and military applications.

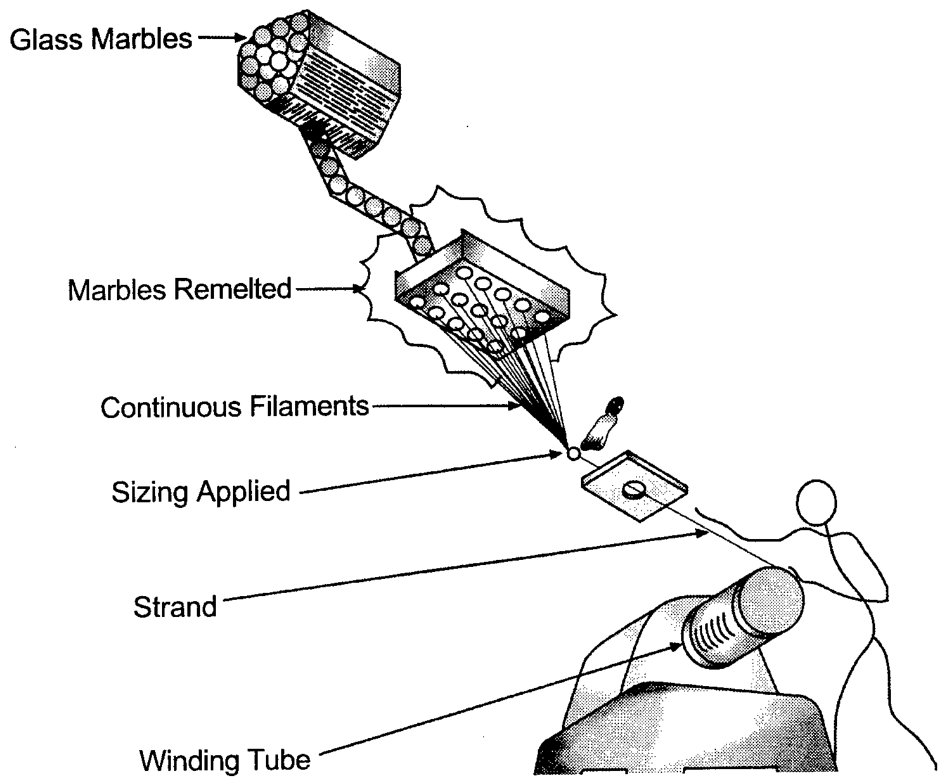


FIGURE 7. FIBERGLASS MANUFACTURING PROCESS

Glass fibers are extremely fragile and abrade easily when processed. This problem is especially evident in processes such as weaving, although any handling or moving process will cause abrasion of the glass fibers. To guard against loss of strength, which depends strongly on surface defects that might be caused during handling, a chemical size (or coating) is applied to the fibers. This size protects the fibers during handling and also holds the individual filaments together. Usually the size is temporary and a finish is added after the size is removed; however, in some cases the size also acts as a finish. The finish improves the compatibility of the fiber with the matrix.

The use of a coupling agent can have a significant effect on the mechanical properties of the composite. Coupling agents can be thought of as bridges connecting the reinforcement and the matrix. Changes of over 100% in the composite tensile, flexural, or compressive strength with different choices of coupling agents are not uncommon for dry specimens. Because glass fibers are somewhat sensitive to moisture, the proper bonding of the glass with the matrix can also improve the mechanical properties in adverse environments. Therefore, both part usage and the matrix to be used should be known before specifying the fiberglass and finish.

2.3.2 Carbon and Graphites.

By far the most common reinforcement for plastics in ablative and structural-composite applications has been fiberglass. Although they have outstanding strength characteristics and low weight, they are relatively low in elastic stiffness. For this reason, beginning in 1971, experimental work was carried out on the thermal conversion of various organic precursor materials into carbon and graphite fibers and fabrics. Five years later carbon and graphite cloth were in commercial production for extensive use in the aerospace, military, and commercial industries.

Carbon or graphite fibers are produced when an organic precursor material undergoes pyrolytic degradation. The commonly used precursor materials include polyacrylonitrile (PAN), rayon, and pitch. PAN-based fibers are high-strength (low-modulus) fibers, and pitch fibers are high-modulus (low-strength) fibers. Manufacturing process for producing carbon fibers is shown in figure 8.

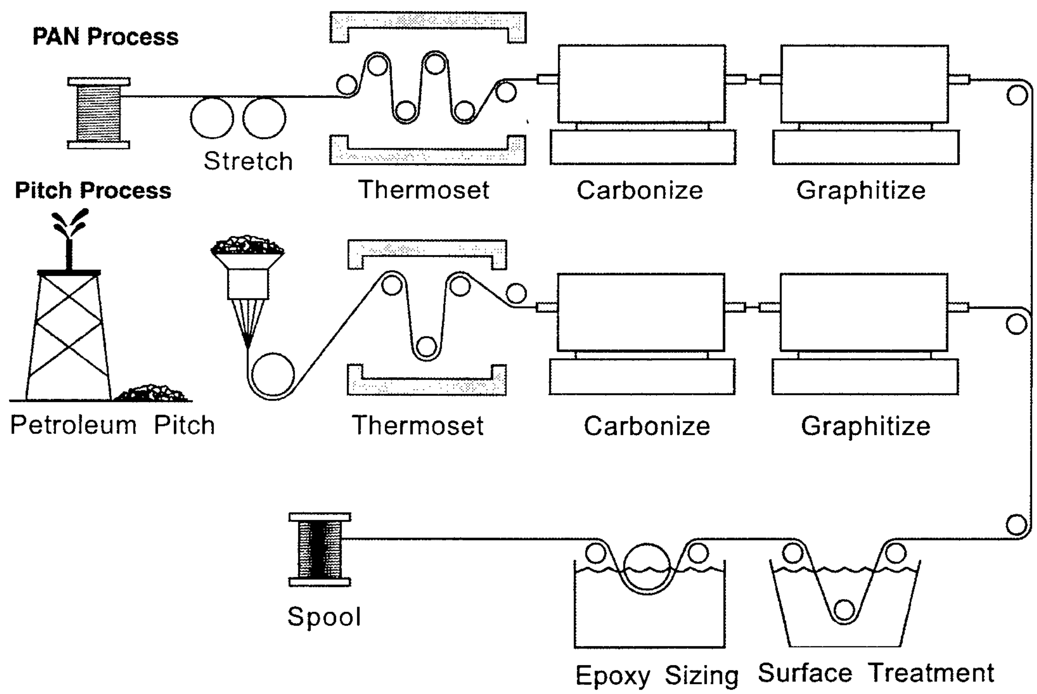


FIGURE 8. CARBON FIBER MANUFACTURING PROCESS

Although the names carbon and graphite are used interchangeably when relating to fibers, there is a difference. Typically PAN-based carbon fibers are 93% to 95% carbon by elemental analysis, whereas graphite fibers are usually 99 plus percent. The basic difference is the temperature at which the fibers are made or heat treated. PAN fibers are produced at about 240°F while higher-modulus graphite fibers are graphitized at 345 to 545°F.

Carbon fibers can be long and continuous or short and fragmented. They can be directionally or randomly oriented, and they can be dispersed in thermoplastic or a thermosetting material (matrix). Each fiber form has its limitations. In general, short fibers are less expensive and fabrication costs the lowest, but the mechanical properties of the resulting composite are lower than for composites obtainable with longer continuous fibers.

Some graphite fibers are produced commercially in the form of yarn (compared with a monofilament) for reasons of economic manufacture and for the fabrication of composite articles. A yarn is used as the reinforcement when maximum composite strength is desired as a filament-wound or unidirectional-tape laminate. The strength of individual filaments in a yarn is not significantly greater than that of similar filaments in a cloth when both are measured in short-gage lengths.

The predominate commercial market for graphite fibers is in the form of yarn as opposed to a single-strand (monofilament) material. When maximum composite strength is desired, yarn may be applied in a filament-wound or unidirectional-tape laminate method. The strength of individual filaments in a yarn is not significantly greater than that of similar filaments in a cloth when both are measured in short-gage lengths.

The unique characteristics of carbon and graphite cloths make them versatile materials for use in high-temperature laminates. With excellent thermal stability and strength at temperatures to 450°F coupled with low density, they offer ideal materials for ablative components.

Where the ultimate in performance or weight reduction is required, continuous carbon fibers are the preferred reinforcement. Continuous fibers are also specified where thermal expansion must be kept to very low levels or where matching the expansion characteristics of an adjoining part made from another material is necessary. Graphite fiber may be manufactured over a wide range of strength and modulus. The kind known as the intermediate type provides outstanding strength and modulus at a reasonable price.

2.3.3 Aramid (Kevlar®).

Introduced commercially in the 1970's, aramid is an aromatic organic compound of carbon, hydrogen, oxygen, and nitrogen. Aramid fiber is produced by spinning long-chain polyimide polymers using standard textile techniques. This low-density, high-tensile strength, low-cost fiber produces tough impact-resistant laminates with about half the stiffness of graphite. Because of the low compressive properties of aramid composites, due to poor coupling of resin matrices to the aramid fibers, applications are either secondary structures or tension critical as is the case with filament-wound overwraps of rocket motor cases. Commercially available aramid fibers include Kevlar® 29, Kevlar® 49, and Nomex.

The fibers were originally developed to replace the steel in the radial tires in order to save weight and increase strength and durability. Kevlar is typically used in high-performance composite

applications where critical factors dictate light weight, high strength and stiffness, vibration dampening, and damage and fatigue resistance.

2.3.4 Boron.

Boron fibers are produced by depositing elemental boron over a tungsten substrate using chemical vapor plating. When a silicon carbide coating is applied over the boron filament, it is referred to as a borsic filament. Boron has been used in military aircraft. Boron filaments are much larger in size compared to glass, carbon, and aramid fibers and are also much stronger in compression.

2.3.5 Ceramic.

Most ceramics are composites in the sense that they contain more than one discrete crystalline or amorphous, glassy phase; therefore, it is customary to refer to such structures as monolithic because of their mechanical behavior. Fibrous ceramic composites are of significant importance due to their enhanced mechanical properties and high-temperature applications. However, their use is not wide spread in typical aerospace applications.

2.4 MATRIX MATERIALS.

The matrix in a composite performs two major roles. First, it transfers loads to the reinforcement. Secondly, it protects the reinforcement from adverse environmental effects.

There are essentially three classes of matrix materials—organic polymers, metals, and ceramics. The composites that are currently used in aircraft are usually polymeric matrix composites. The selection of the matrix material is dependent on the maximum service temperature for the considered application. Polymeric matrices are applicable to a maximum of 600°F of continuous exposure, depending on their chemical characteristics. Among metals, most of the aluminum alloys are applicable up to 500°F of continuous exposure, with a short-term exposure capability up to 650°F. Titanium is capable of withstanding up to 1000°F on a continuous basis, with a short-term exposure capability up to 1200°F. Ceramics are capable of withstanding temperatures in excess of 2000°F.

Of the three matrix categories, the polymeric matrices are the lowest in density and yield the lightest composites. Therefore, when the application service temperatures are below their temperature limits, these are generally the best choice. For example, in civil aircraft applications most of the structural parts are restricted to temperature exposures below 200°F. Epoxy polymeric matrix composites possess the potential to replace metals in these aircraft structures. Exceptions are the engine components and parts in the path of the exhaust which experience temperatures in the range of 250-500°F for which bismaleimide and polyimide polymers are more suitable. Another consideration in the selection of the matrix material for composites is the processing requirement imposed by the material. Polymers, metals, and ceramics lend themselves to vastly different processing procedures that affect manufacturing costs and are a major material

selection criterion. It will suffice to say that, at present, polymeric matrix composites are the most economical for manufacturing composite parts.

Based on the above observations, subsequent discussions are restricted to polymeric matrix composites. Polymers are divided into two categories—thermosets and thermoplastics.

Thermoset materials are those materials which require a cure cycle, either at an elevated or ambient temperature over some period of time to set or form. Once they become set, they in fact are set, and form the basis of the plastic or resin matrix material. Thermoplastics on the other hand are already solids. (The most common examples are some of our kitchen or household utensil products.) They can be formed or reshaped by the addition of heat and pressure. Theoretically, this forming and reshaping can be done many times, whereas the thermostat materials are formed once and they are set.

Thermoplastics are softened by heating and set again on cooling without undergoing a chemical change. This physical change is reversible; for example, by the application of further heat, they revert to their original state. They can, therefore, be molded like wax or metal by heating and cooling in a mold. Sample thermoplastics include polyetheretherketone, polyethersulfone, nylon, polyethylene, polystyrene, and polyvinyl chloride. Some of these are currently being evaluated for future aircraft applications.

Both the thermoplastic and thermoset plastics are composed of molecular chains. While the molecular chains of the thermoset material are interconnected with chemical bonds (called crosslinks), the thermoplastic chains are not. Because of their differing chemical structure, thermosets and thermoplastics have unique properties. Although thermosets cannot be remelted because of the crosslinking, thermoplastics can. Some thermosets can be ablative, whereas thermoplastics cannot because they would melt. Thermosets are usually more rigid than thermoplastics and also exhibit generally higher temperature performance, although, some high-performance thermoplastics are now equal to the most common thermosets in temperature capability.

Finally, while thermosets require a cure to achieve crosslinking and a useful state, thermoplastics are heated, molded to the desired shape, and then cooled to the useful solid state. As a result, thermosets usually require much longer processing times. However, current thermoset polyesters used in the automobile industry have cure times of 1 or 2 minutes, which are not much longer than some thermoplastic cycle times. On the other hand, aerospace epoxies usually require multihour cure cycles. Frequently, a major limitation is the heat-up time required for the molding equipment and the molds. If the tooling has its own built-in heaters, the heat-up time can be significantly reduced.

2.4.1 Thermosets.

2.4.1.1 Polyester Resins.

For many years, polyesters have dominated the markets for commercial fiberglass reinforced composites. To avoid confusion, the term fiberglass will only be used in this text to mean the fibrous reinforcement made of glass. Sometimes the term fiberglass has been used to indicate the entire composite material made from polyester resin with a fiberglass reinforcement, such as a fiberglass boat. Examples of major applications for reinforced polyesters include boat hulls, shower enclosures and tubs (spas), air conditioner and automotive ducting, car bodies, building wall and roof panels, molded furniture, pipes, and railroad cars. Polyester resins are generally the lowest-cost matrices for composites, thus accounting for their wide usage. However, due to their lower temperature capability, lower weathering resistance, and lower physical properties compared to other resins, their use in advanced composites has been limited.

2.4.1.2 Epoxy Resins.

The most common matrix for advanced composites and for a variety of demanding applications is epoxy. Epoxies have taken this major role because of their excellent adhesion, strength, low shrinkage, corrosion protection, processing versatility, and many other properties. Epoxies may be more expensive than polyesters and may not perform as well in high-temperature applications as polyimides but overall their properties are excellent. As mentioned at the beginning of this section, the matrix in a composite can be thought of as performing two major roles: transferring loads to the reinforcement and protecting the reinforcement from adverse environmental effects. Generally, epoxies do a fine job. In addition, the epoxy group provides for good adhesion with the reinforcement or with the surface of another material. The advantages and disadvantages of epoxies are listed in table 1.

The properties of the crosslinked polymer are more dependent upon the choice of curing system in epoxies than in polyesters, so both the nature of the epoxy and the curing system must be understood.

One of the reasons for the widespread use of epoxy systems in advanced composites is the adaptability to manufacturing methods. The large variety of epoxy types and cure systems commercially available allow the cure rates and performance to be tailored.

High-performance aircraft applications use a material form called a prepreg in which fibers are sold preimpregnated with resin. The fibers can be unidirectional or woven. These prepregs can be made using epoxies and cure systems that are not reactive at freezer temperatures to provide long storage times for customers, yet can be cured quickly at high temperatures and provide service temperature capabilities of 250 to 350°F (121 to 177°C).

TABLE 1. PROPERTIES OF EPOXIES

ADVANTAGES	RATING
Adhesion	Outstanding
Strength	Excellent
Corrosion Protection	Outstanding
Chemical Resistance	Excellent
Shrinkage on Cure	Very Low
Electrical Properties	Excellent
Versatility	Excellent
Toughness	Good
Toxicity (cured)	None known
Taste (cured)	None
Heat Resistance	Good
Weather Resistance	Excellent for Protection
Color/ Odor	Good
Fatigue Strength	Excellent
DISADVANTAGES	**RATING**
Cost	Medium to High
Ease of Handling	Medium to Difficult
Toxicity (uncured)	Problems

Epoxy systems have also been developed for rapid cure even under cold conditions such as gluing reflectors to road surfaces. In general, the temperature capabilities of the cured resin will be similar to the cure temperature. Room temperature cured resins will soften somewhat at temperatures just above room temperature. High temperature capability requires high-temperature cures.

In part, the high degree of crosslinking needed to achieve temperature performance reduces the toughness of epoxy resins. However, recent advances have boosted the level of toughness of composites based on epoxies to equal or surpass the toughness of other resin systems (such as thermoplastics). This has been achieved with little loss in temperature performance. In addition, these tougher systems can be processed like the earlier, brittle systems. In this way, high-performance composites can be fabricated with existing facilities and equipment designed for thermoset chemistry without the modifications needed to handle a different curing technology.

2.4.1.3 Phenolics.

Phenolic thermoset resins have limited but important uses as composites. Phenolics have been used for many years as a general, unreinforced thermoset plastic in applications such as electrical switches, junction boxes, automotive molded parts, consumer appliance parts, handles, and even billiard balls. Because phenolic resins are quite brittle and have high shrinkage, almost all

applications have fillers added. The principal use for long-fiber reinforced phenolic resins is for rocket nozzles and nose cones where the ablative nature of the phenolic can be utilized. Other uses include high-temperature aircraft ducts and muffler repair kits, both are applications where temperature is a factor. Also, some wings and fins for rockets use phenolic matrix materials.

2.4.1.4 Bismaleimides and Polyimides.

Bismaleimide resins (BMI's) posses many of the same features as do epoxies, such as fair handleability, relative ease of processing, and excellent composite properties. They are superior to epoxies in maximum hot/wet temperature use, extending the safe in-service temperature to 200 to 220°C (400 to 430°F) or higher. Unfortunately BMI's exhibit many of the same deficiencies (and more) as do epoxies. They have an even lower strain to failure and are quite brittle. Damage tolerance is generally comparable to commercial aerospace epoxy resin systems.

Polyimide resins are available with a maximum hot/wet in-service temperature of 260°C (500°F) and above. Unlike BMI's, these cure by a condensation reaction that releases volatiles during cure. This poses a significant problem because of their released volatiles and subsequent voids caused in the laminate. Work continues to progress in these areas of concern, specifically with volatile release during cure. These resins will produce good quality composites but tend to be somewhat brittle.

Polyimides are typically categorized by their high-temperature capabilities well into the 450 to 500°F range for extended periods. PMR-15 is a common product in this family of resins using a crosslinked reaction. Polyimide resin systems exhibit excellent high-temperature resistance for typical use in the aircraft and aerospace industries.

2.4.2 Thermoplastics.

Several unique thermoplastic resin materials have been developed for use in composite materials. These resins generally have inherent thermal and mechanical capabilities beyond the conventional industrial thermoplastics and, in some cases, better than the polyester and epoxy thermosets. Improved toughness or impact resistance is another attribute over thermoset materials. Toughness is becoming increasingly important as damage tolerance becomes a major issue in aircraft design.

The high-performance thermoplastics are usually much more costly. The most significant of these high-performance thermoplastic matrices developed to date include the following: polyetheretherketone (PEEK) and related molecules and the thermoplastic polyimides already discussed. The development of these high-performance thermoplastic matrices is an area of current research and hence additional resins are to be expected.

As previously discussed, the inherent differences between thermoplastics and thermosets give each type of resin some distinct advantages over the other (see table 2). Thermoplastics do not require reactive cure cycles but are supplied as essentially nonreactive solids which require only heat and pressure with subsequent cooling to form them. This has obvious savings in processing time and equipment costs, but for some processes there is a requirement for the resin to diffuse quickly to coat the reinforcement during the relatively short period of time that the resin has low viscosity (high fluidity).

TABLE 2. GENERAL COMPARISON, THERMOSET VERSUS THERMOPLASTIC

	THERMOSET	THERMOPLASTIC
Raw Material Cost	✓	
Shelf Life		✓
Toughness		✓
Reusable Scrap		✓
Moisture Resistance		✓
Strength/Stiffness	✓	✓
Creep	✓	✓
Solvent Resistance	✓	✓
Temperature Resistance	✓	✓
Fatigue	✓	✓
Postformable	✓	✓

On the other hand, cured thermosets have much higher molecular weights because all the polymer chains are tied into one large network. This network results in improved strength and modulus but diminished elongation and toughness. Furthermore, fibrous sheets already impregnated with resin (prepregs) which are made from thermoplastics have an infinite shelf life compared to the limited life of thermoset prepregs. The thermoplastic prepregs are stiff and without drape or tack which are present in the thermosets before curing. It is obvious, therefore, that in the choice of thermoplastic versus thermoset resin, several trade-offs and compromises must be made. A summary of these trade-offs is given below in table 3.

A major advantage of using conventional thermoplastics as the matrix, versus using a thermoset matrix, is in the processing. The number of processing methods is very large with thermoplastics, and the fabrication times are generally much less than with thermosets. However, it is appropriate to mention here that the major industrial thermoplastics processes fabricate parts using conventional, industrial thermoplastics composite materials such as extrusion, injection molding, thermoforming, rotomolding, and blow molding.

TABLE 3. PROPERTY COMPARISON, THERMOSET VERSUS THERMOPLASTIC

	THERMOSET	THERMOPLASTIC
PROPERTY	(931 EPOXY*)	(APC-2 PEEK*)
Melt Viscosity	Low	High
Fiber Impregnation	Easy	Difficult
Prepreg Tack	Good	None
Prepreg Drape	Good	Poor
Prepreg Stability at 0°F	6 mos.-1 yr.	Indefinite
Processing Cycle	1-6 hrs.	15 sec-6 hrs.
Processing Temperature	350°F	700°F
Processing Pressure	90 psi	>200 psi
Mechanical Properties	Good	Good
Environmental Durability	Good	Exceptional
Damage Tolerance	Average	Good
Database	Large	Average

* Fiberite Materials

Thermoplastic (TP) composite production is similar in many respects to sheet metal forming processes. Sheet metal-forming technology can be applied to thermoplastic production. The process starts with a form of material supplied from the manufacturer (thin single-ply fabric or unidirectional material on a roll and flat sheets of multiple-ply fabric or unidirectional material). The technician would heat these precut shapes beyond their softening temperature in an oven or other unit, and then place them in a hard tool (match-tooling) which would be held at a temperature slightly below the flow temperature. The tool is then closed and the appropriate pressure is applied for cure. Because this is a thermoplastic material, long cure times are not necessary and the tool can be opened (slightly cooled) soon thereafter. The formed part can be removed from the tool and handled soon after for subsequent trim operations. Scrap can be reused due to the nature of TP's making this process extremely attractive financially in terms of in-process scrap reduction.

This simple description embodies most conventional thermoplastic composite production applications. Thermoplastic reinforcements are obtainable in a variety of forms, some of which are not forgiving in nature prior to processing. Consequently, well engineered, robust tooling and significant pressure may be required to mold these forms from a boardy stage through the melt point and into a molded composite shape with specific dimensions. Pressure requirements reaching 200 psi or more are common and can be obtained via a hydraulic press or autoclave. Temperature requirements range from 400 to 800°F depending on the thermoplastic ingredients. Platen presses, heat blankets, ovens, and autoclaves can all provide adequate temperature for processing, but some are more efficient than others depending on part geometry and economics.

Epoxy tooling can be used in limited-run prototype situations, but by and large the tooling material of choice is aluminum or steel for any high-temperature production applications.

2.5 CORE.

Aerospace sandwich structure consists of two skin facesheets attached to a core using adhesive. There are many materials utilized in the development of a core. The most common type of core is a honeycomb. Depending on the design parameters of the part, the aerospace industry may utilize either metallic or nonmetallic honeycomb material. A honeycomb core is made from materials such as aluminum, fiberglass, or Nomex. The original honeycomb core material was made with paper.

2.5.1 Core Materials.

Choosing the right core material is critical to the composite's performance. Traditional single skin structures require high-density laminates to insure strength and stiffness. Lightweight core materials include wood, foam, and honeycomb.

Wood has been available for a long time, and it serves as a good core material in many modern composites. It is stiff and strong with high-shear properties. However, its variations in density and physical properties, difficulty in fabricating, and vulnerability to the environment limit its application.

Extruded polystyrene is a low-density insulating foam. Because polystyrene is easily cured, it is often the choice for parts of the structure requiring detailed shaping.

Other core materials such as rigid foams (usually polyvinyl chloride (PVC) or polymethacrylimide foams) are being used more often. These foam cores can be preformed or precut to the dimensions desired and then bonded to the face panels as would be done with other core materials. Foams can also be injected between the face panels and cured in place, although some uniformity problems are often encountered in this method. Foams are used in many applications but the most prevalent are for radar transparencies and insulation.

The mechanical properties of all honeycomb materials increase with increasing density so trade-offs with critical weight applications are often necessary. Honeycomb materials are anisotropic (directional) in their properties so this must be considered in designs using honeycombs. The cell shape largely determines the formability of the honeycomb and the cell size has some relationship to bondability but is secondary in other performance aspects.

There are three cell shapes which are commonly made: hexagonal, overexpanded hexagonal (rectangular), and flexible. The overexpanded cell is formed by expanding the hexagonal beyond the normal amount. The cells become rectangular. This material is formed more easily along the face than hexagonal cell shape material but is less strong in the other direction. The flexible cell

shape material has a lobe-shaped cell which can be easily shaped in all directions but is not as strong as hexagonal.

Honeycomb materials can be trimmed with band saws or serrated knives. They may also be brake or roll formed if made of metal and are heat formed if made of paper, fiberglass, or aramid. They are normally spliced by using a foaming adhesive.

Metal, aramid, and fiberglass honeycomb materials are machined best when cold. Therefore, they are held in place on freeze tables and machined. Chamfered edges can be machined in this manner or, in the case of aluminum, can be achieved by crushing with matched metal molds.

2.5.2 Honeycomb Manufacturing.

Honeycomb is made primarily by the expansion method. The corrugated process is most common for the high-density honeycomb materials.

2.5.2.1 Expansion Method.

The expansion method for the honeycomb fabrication (see figure 9) begins with stacking sheets of web material on adhesive node lines which have been printed. The adhesive lines are then cured to form a HOBE (Honeycomb Before Expansion) block.

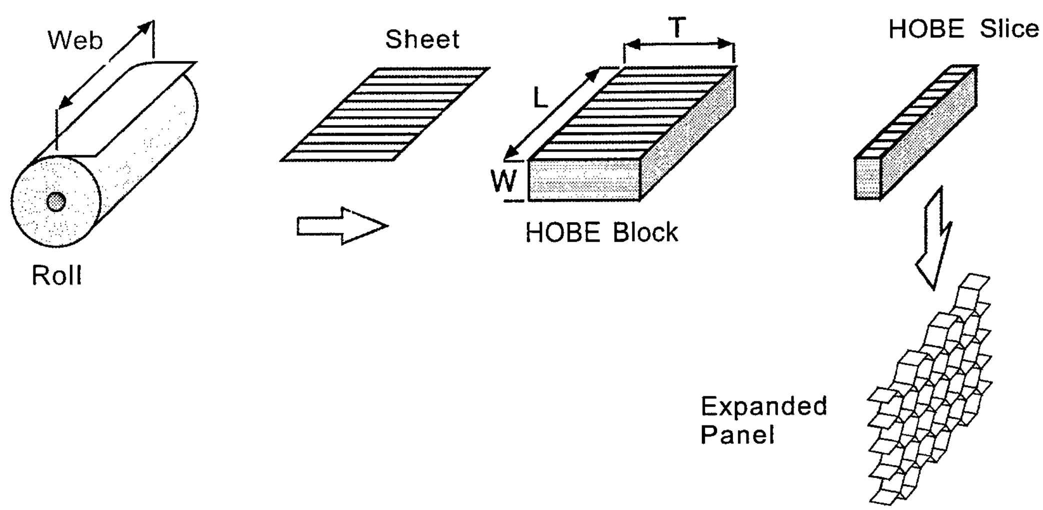


FIGURE 9. EXPANSION PROCESS OF HONEYCOMB MANUFACTURE

The HOBE block itself may be expanded after curing to give an expanded block. Slices of the expanded block to the desired T dimension may be taken. Alternately HOBE slices can be cut from the HOBE block to the appropriate T dimension and expanded.

Each HOBE slice is then expanded to the desired cell shape and yields the expanded panel. The expanded panels are trimmed to the desired L (ribbon direction) and W dimension (transverse to the ribbon). The L, W, and T dimensions are expressed in inches.

2.5.2.2 Corrugated Process.

The corrugated process of honeycomb manufacture (see figure 10) is normally used to procure products in the higher density range. In this process, adhesive is applied to the corrugated nodes, the corrugated sheets are stacked into blocks, the node adhesive cured, and panels are cut from these blocks to the required core thickness. The dimensional terminology for blocks made by the corrugated process is identical to that for expanded honeycomb.

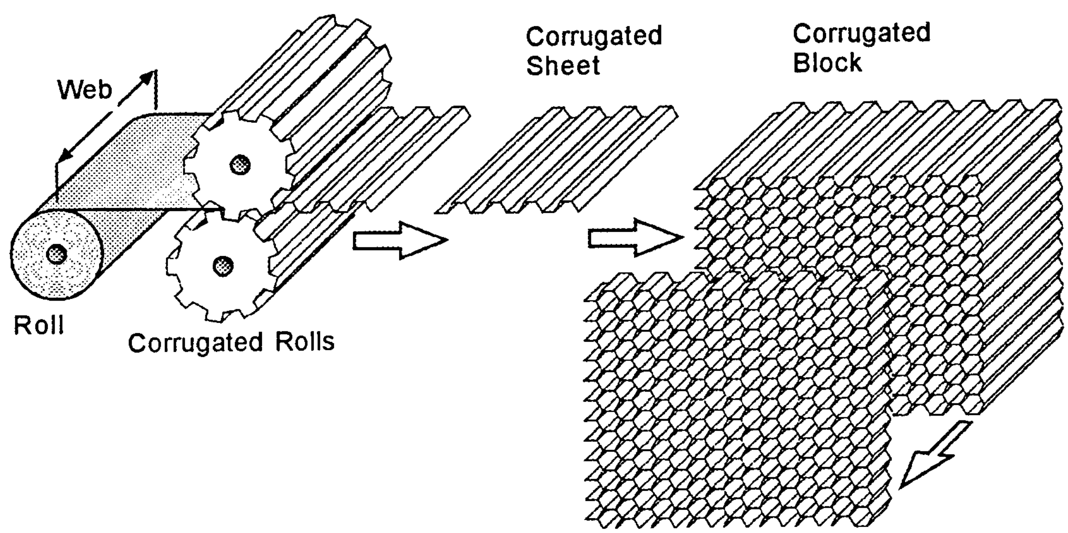


FIGURE 10. CORRUGATION PROCESS OF HONEYCOMB MANUFACTURE

2.5.3 Honeycomb Configurations.

There are five basic honeycomb core configurations, four of which are shown in figure 11.

2.5.3.1 Hexagonal Core.

The standard hexagonal honeycomb is the basic and most common cellular honeycomb configuration and is currently available in all metallic and nonmetallic materials.

2.5.3.2 Ox-Core.

The Ox configuration is a hexagonal honeycomb which has been over-expanded in the W direction and provides a rectangular cell configuration which facilitates curving of the form in the L direction. The Ox process increases W shear properties and decreases L shear properties when compared to a hexagonal honeycomb.

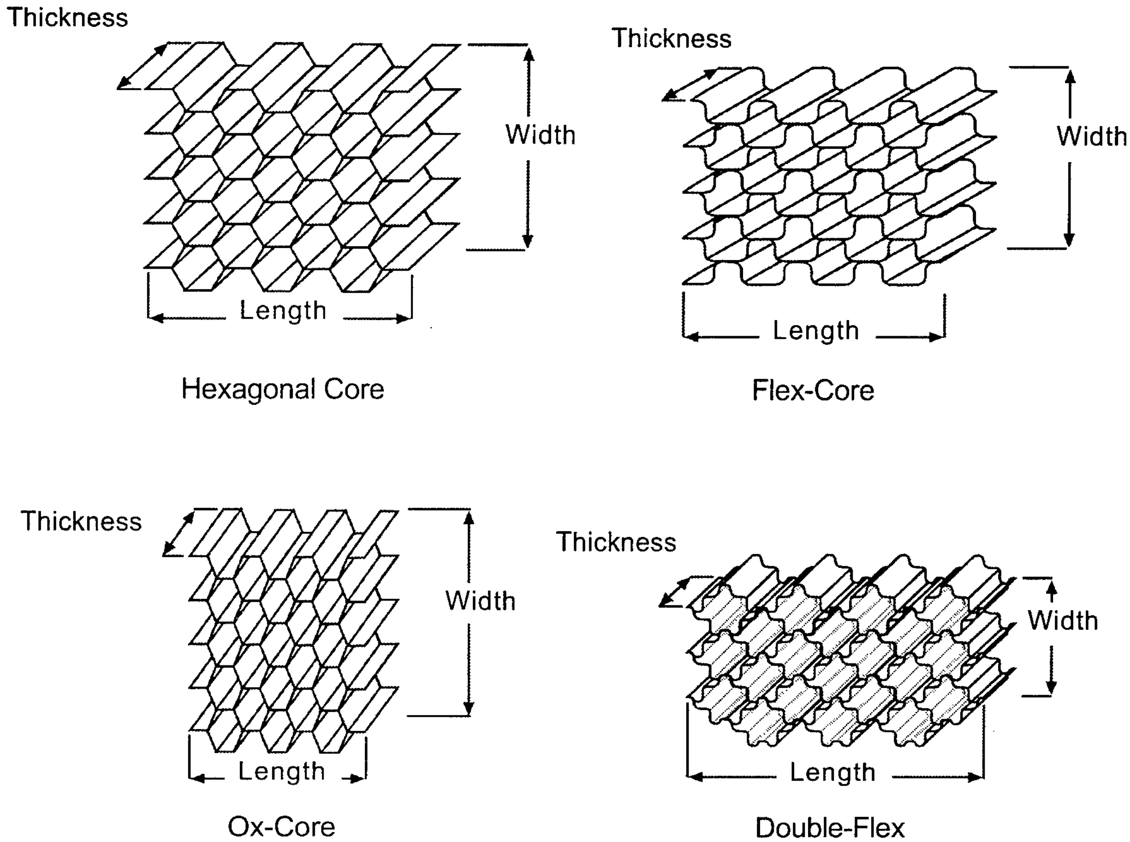


FIGURE 11. HONEYCOMB CORE CONFIGURATIONS

2.5.3.3 Flex-Core.

The Flex-Core cell configuration provides for exceptional formability in compound curvatures with reduced anticlastic curvature and without buckling the cell walls. In dealing with curvatures with very tight radii, Flex-Core seems to provide higher shear strengths than a comparable hexagonal core of equivalent density. Flex-Core can be manufactured in most of the materials from which a hexagonal honeycomb is made.

2.5.3.4 Tube-Core.

A Tube-Core configuration provides a uniquely designed energy absorption system when the space envelope requires a thin-wall column or small-diameter cylinder. The design eliminates the loss of crush strength that occurs at the unsupported edges of the conventional honeycomb. A Tube-Core is constructed of alternate sheets of flat aluminum foil wrapped around a mandrel and adhesively bonded. Outside diameters can range from 1/2 to 30 inches and lengths of 1/2 to 52 inches.

2.5.3.5 Double-Flex™.

A Double-Flex is a large-cell Flex-Core with excellent formability and high specific compression properties. Double-Flex formability is similar to a standard Flex-Core.

2.5.4 Types of Honeycomb.

Available honeycomb types, material, and geometry are described in this section.

2.5.4.1 Aluminum Honeycomb.

Aluminum honeycombs are designated in the following example:

MATERIAL	CELL SIZE	ALLOY FOIL	THICKNESS	DENSITY
CR III	1/4	5052	0.002N	4.3

- CR III signifies the honeycomb is treated with a corrosion resistant coating.
- 1/4 is the cell size in fractions of an inch. (Inscribed diameter as shown in figure 12.)
- 5052 is the aluminum alloy used.
- 0.002N is the reference foil thickness in inches, N indicates the cell walls are nonperforated. P indicates perforated, not available in the Flex-Core configuration. Perforated honeycomb is used when the curing of the core-to-skin adhesive results in volatiles which must be vented. Flex-Core may be slotted, if necessary.
- 4.3 is the density in pounds per cubic foot.

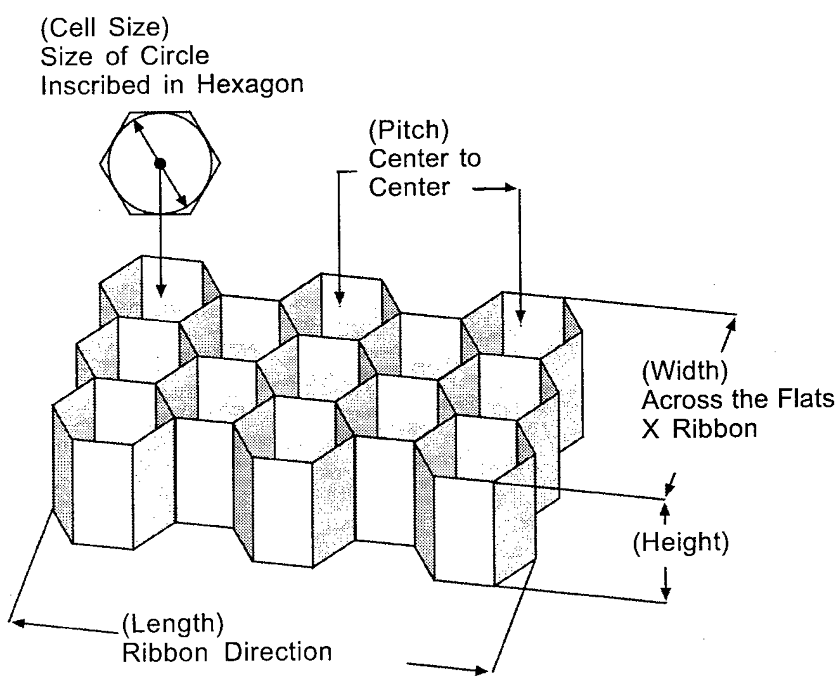


FIGURE 12. HEXAGONAL CORE ANATOMY

2.5.4.1.1 CR III®.

The CR III prefix to the aluminum honeycomb designation indicates corrosion resistant aluminum honeycomb. The CR III coating is placed on the foil before the node adhesive is applied, thereby insuring corrosion protection over the full foil surface area. All of the standard aluminum core types are normally supplied with this corrosion protection.

2.5.4.1.2 5052 Alloy.

Specification grade honeycomb is the 5052 H39 aluminum alloy and is available for general purpose applications in a very wide range of cell size/density combinations in the hexagonal and Flex-Core configurations. Ox-Core and under-expanded core can also be provided upon special request.

2.5.4.1.3 5056 Alloy.

Specification grade honeycomb in the 5056 H39 aluminum alloy offers superior strength over 5052 alloy honeycomb. It is also available in a broad range of cell size/density combinations in the hexagon and Flex-Core geometrics.

2.5.4.1.4 2024 Alloy.

The heat-treatable aluminum 2024 alloy combines high room-temperature properties with increased strength retention at elevated temperatures. It is produced in several cell sizes and densities in the T3 and T81 tempers.

2.5.4.2 Glass Reinforced Honeycomb.

Glass reinforced honeycombs are designated in the following example:

MATERIAL	CELL SIZE	DENSITY
HRP®	3/16	4.0

- HRP refers to the type of material
- 3/16 is the cell size in fractions of an inch.
- 4.0 is the nominal density in pounds per cubic foot.

2.5.4.2.1 HRP®.

HRP is a glass fabric-reinforced plastic honeycomb dipped in a heat resistant phenolic resin to achieve the final density. This product was developed for use at service temperatures up to 350°F. However, it is also well suited for short exposures at higher temperatures. The HRP-

series honeycomb is available in the standard hexagonal configuration, as well as in the two formable geometrics—Ox-Core and Flex-Core.

2.5.4.2.2 HFT®.

HFT is a glass fabric-reinforced plastic which incorporates a Fibertruss® bias weave dipped in a heat resistant phenolic resin to achieve the final density. This material is recommended for use at service temperatures up to 350°F but is well suited for short exposures at higher temperatures. The Fibertruss configuration greatly enhances the shear properties: HFT has a much higher shear modulus than HRP or HRH-10.

2.5.4.2.3 NP®.

NP is a glass fabric-reinforced plastic honeycomb in which the initial web impregnation is a nylon-modified phenolic resin and the final dip coats are polyester resin. This core type is recommended for applications in which the service temperature does not exceed 180°F for extended time periods. The NP series honeycomb is available in the hexagonal and Ox-Core configurations.

2.5.4.2.4 HRH®-327.

HRH-327 is a glass fabric, polyimide node adhesive bias weave reinforced plastic honeycomb dipped in a polyimide resin to achieve the final density. This material has been developed for extended service temperatures up to 500°F with short range capabilities up to 700°F.

2.5.4.3 Aramid-Fiber Reinforced Honeycomb (Nomex®).

Aramid fiber-reinforced honeycomb is designated in the follow example:

MATERIAL	CELL SIZE	DENSITY
HRH®-10	3/16	3.0

- HRH-10 refers to the type of material.
- 3/16 is the cell size in fractions of an inch.
- 3.0 is the nominal density in pounds per cubic foot.

2.5.4.3.1 HRH®-10 (Aramid Fiber).

This product consists of DuPont's Nomex aramid fiber paper dipped in a heat resistant phenolic resin to achieve final density. It features high strength and toughness in a small cell size with low density and a nonmetallic core. It is available in the hexagonal, Ox-Core, and Flex-Core configurations. It is recommended for service up to 350°F.

2.5.4.3.2 HRH-310 (Aramid Fiber).

HRH-310 is made from the same aramid fiber paper described above, except it is dipped in a polyimide resin to achieve the final density. It is produced in both hexagonal and overexpanded cell configurations. Outstanding features are its dielectric and loss tangent properties.

2.5.4.3.3 Special Honeycomb HFT-G.

HFT-G is a bias weave graphite fabric-reinforced plastic honeycomb dipped in a heat resistant phenolic resin to achieve the final density. This product was developed for use at service temperatures up to 350°F. However, it is well suited for short exposures at higher temperatures. HFT-G is also available dipped in a polyimide resin for applications requiring service temperatures in excess of 350°F. The mechanical properties of HFT-G are comparable to 5052 aluminum core and have very low coefficients of thermal expansion.

2.5.4.3.4 HRH-90.

This is a woven graphite-reinforced honeycomb dipped in a 350°F cure modified epoxy resin to achieve the final density. This material has been developed for demanding space applications that require very low coefficients of thermal expansion.

2.5.4.3.5 Acousti-Core®.

Hexcel has developed methods for introducing acoustical fiberglass batting into the cells for sound absorption. This batting improves the sound absorption characteristics of the honeycomb core and also results in two side benefits: the smoke generated in the National Bureau of Standards (NBS) smoke chamber is greatly reduced with the aramid Acousti-Core materials and thermal conductivity is reduced due to the batting.

2.6 MATERIALS HANDLING AND STORAGE.

Use of improperly stored adhesives, sealants, or prepregs may result in structurally unsafe aircraft components. At best, costly rework operations would be involved; at worst, the loss of an aircraft. It is important that the applicable specification and/or manufacturer's detail requirements and recommendations for shelf life, storage temperature, and special tests (both as received and after mixing components) be followed. All personnel concerned with procurements, handling, storage, and usage should be keenly aware of the critical nature of the design function of these items and be alert to potentially unsatisfactory conditions regarding storage temperatures, storage life, and storage conditions. This is particularly true for manufacturing and inspection personnel.

The correct handling and storage of composite materials such as prepregs and adhesives is of critical importance. Because of their chemical composition, bonding adhesives tend to weaken

rapidly when left in the open air. Therefore, when not in use, materials must be stored in airtight plastic bags in a refrigerated freezer. The storage freezer must have temperature and humidity controls. While in the freezer, the prepreg material is protected from moisture by a vapor-proof plastic bag. While in the freezer, rolls of material must be stored by supporting them on their winding cores to prevent roll distortion and fiber damage.

Thermosetting materials have a specific period of time whereby the material can be exposed to elevated temperature conditions before it becomes unsafe to use. In effect, they tend to cure over time and become unusable. Thermosetting materials, resins, or a preimpregnated material (prepregs) are stored in cold temperatures in a freezer. The requirements are delineated by the material supplier.

When materials are removed from the cold storage environment, a log is usually kept that would indicate the number of hours that the materials are out at room temperature during fabrication. Each material manufacturer describes in their data sheet a specific time that their materials can be exposed to room temperature before they lose their ability to be used as a structural matrix.

In general, adhesives, sealants, and prepregs are stored at controlled temperatures which can be divided into three ranges: (1) those with ambient storage temperature, (2) those requiring refrigeration at about 40°F maximum, and (3) those requiring a deep freeze of 0°F or below. Most of these materials also have limited shelf life. When the material is taken out of the freezer, the material should not be removed from the sealed protective wrapping until the condensation of moisture on the exterior of the package ceases. For tape materials up to 12 inches wide, the warm-up period is a minimum of 2 hours. Broad goods, over 12 inches wide, require a minimum 16-hour warm-up.

The differences in storage and handling requirements between metals and composites (thermosets) are shown in figure 13. In the case of thermoplastic materials, they are already cured or set. However, their surface should be protected and in many cases they could have some affinity to environmental conditions, such as heat. If the materials are dry and bulky, reinforcements such as glass fibers, strands, or rolls without any resin, the fibers may have some surface material applied which assists in the wetting or the binding of the fiber to the resin matrix. These materials should be kept covered in a dust-free area so that their surfaces do not become contaminated. The nonproductive materials such as vacuum bags, films, sealants, valves, and breathers require minimal storage supervision. However, as a rule the oldest inventory should be used first.

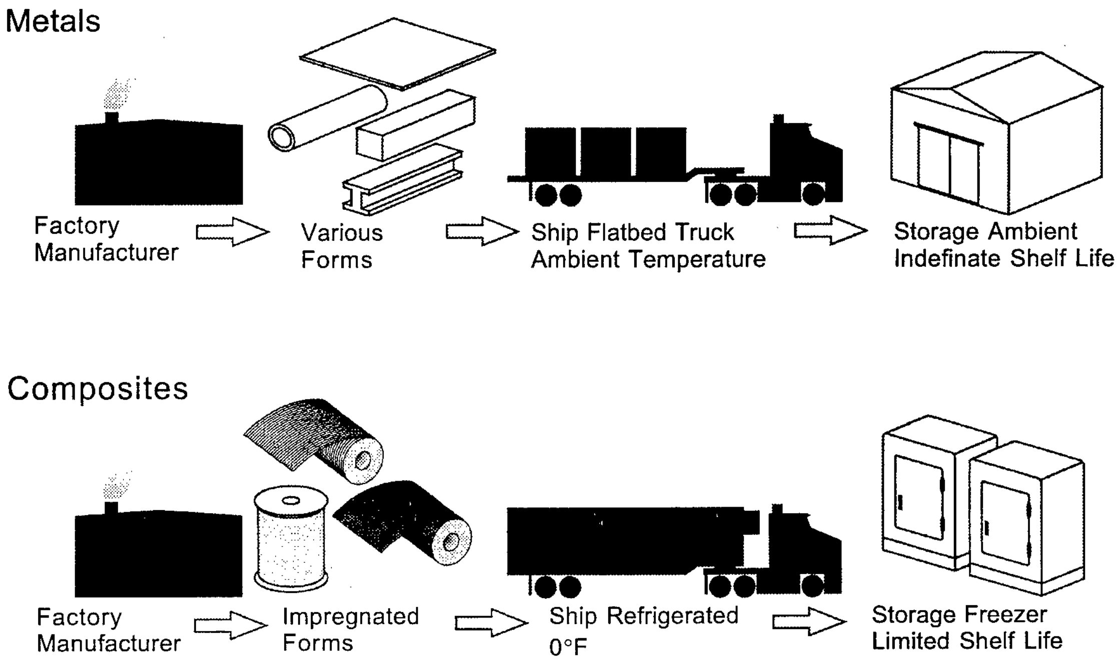


FIGURE 13. COMPARISON OF MATERIAL HANDLING AND STORAGE

2.7 MATERIAL TRACEABILITY.

We have to understand that catalyzed thermosetting materials can be exposed at room temperature to the environment for a limited period of time. This knowledge of material expiration limits is the basis of material traceability. Traceability is the recorded tracking of the materials during the part manufacturing process. This record keeping is usually on the shop work order document that travels with the composite part as it is being manufactured. The thermosetting material usually is identified by batches or lots that are established by the material supplier and comply with the suppliers quality assurance inspection and certifications. Traceability is necessary so that if a part failure occurs, it can be traced back to the parent lot or batch of material. An example scenario where this might apply could be in the shipping of prepreg across great distances. During a 3- or 4-day trip it is possible that the material could be exposed to temperatures in a truck or sitting on someone's shipping or receiving dock where the temperature exceeds that required for safe storage. It is necessary to have this occurrence documented and traced before the materials are put into service. An example of a tracking label might look like the following:

ACCEPTABLE MATERIAL THIS MATERIAL HAS BEEN INSPECTED PER INSPECTION INSTRUCTION 503 AND ACCEPTED FOR USE. MATERIAL ______________________________ LOT ________ ROLLS ____________ LIMITATION SIKORSKY AIRCRAFT DATE: JULY 15, 1978

This label will be attached to boxes or containers used to store adhesives/prepregs. This label will give evidence of receiving acceptance and a material time out record will be placed on the container or box indicating usage.

Adequate inspection and quality assurance procedures must be employed during the prepreg screening, manufacture, and service maintenance of composite structures used in civil aircraft structures. The composite prepreg quality is achieved by screening all incoming material for their physical, chemical, and mechanical properties using procedures contained in the particular material specification. All manufacturing processes are monitored and documented according to the processing specification. The fabricated parts are subjected to ultrasonic and x-ray inspections to assure adequate quality. During the service life of the aircraft, inspection procedures are established and performed to assure continued structural integrity of the various composite components.

Polymer matrix prepregs must be handled properly and stored in accordance with established requirements to ensure retention of prepreg quality. Prepreg storage requirements and shelf life are established based on a study of periodic chemical fingerprints and associated physical and mechanical properties when the prepreg is stored in a controlled environment. The period of time for which the material is outside the freezer must be documented in an "out time" ledger. A typical freezer inventory card is shown in figure 14, while typical data that is recorded is shown in table 4.

FREEZER INVENTORY CARD

Material

Ums No.

Date Received — Batch No.

Date Expires — Roll No.

Retest Date — Freezer No.

Extension Date — Card Of

A.M.			P.M.		
Date	In	Out	Date	In	Out

FIGURE 14. FREEZER INVENTORY CARD

TABLE 4. TYPICAL MATERIAL DATA RECORDED IN A PRODUCTION ENVIRONMENT

ITEM NO.	INFORMATION
1	Material ID
2	Supplier designation
3	Lot or batch number
4	Roll number
5	Date manufactured
6	Date received
7	Date and time placed in cold storage
8	Dates and time removed from cold storage
9	Dates and time returned to cold storage
10	Laboratory report numbers
11	Dates released by quality assurance

3. TOOLING.

3.1 INTRODUCTION.

Tooling or molds are used to define the shape of the composite part and one or more of the surfaces, depending on the type of tooling. The requirements for tooling are conceptually quite simple. The tooling must provide a mechanism to give a part the desired shape at the end of the mold cycle. The molds for lay-up can be made of composite, metal, or several other materials. It is important that the mold holds its shape. Proper release agents must be added to ensure release from the mold.

3.2 TOOLING FEATURES.

The tooling used to cure composites is subjected to high pressures and temperatures. Because of these environmental conditions, special materials are required for composite fabrication tools. The tools used for the autoclave or oven curing of composite parts are called bond tools or bonding fixtures (see figure 15). The materials used to fabricate bond tools are numerically controlled (N/C) machined steel, N/C machined aluminum, electroformed nickel, and high temperature epoxy. Some materials that are being developed for use as bond tools are: vapor formed nickel, graphite/epoxy, and machinable graphite .

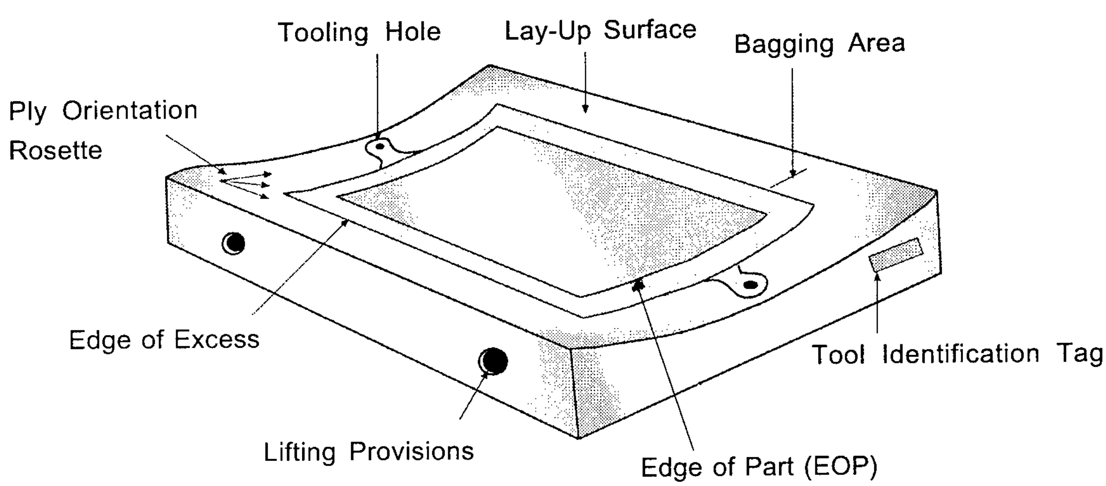


FIGURE 15. TYPICAL TOOL FEATURES

The N/C machined steel or aluminum bond fixtures are becoming more common in the aerospace industry. The process of producing an N/C machined bond fixture involves the rolling or forming of the metal sheet to the approximate shape followed by the machining of the tool to the exact contour requirements. If a welded backup structure is to support the tool, the backup structure is attached to the formed sheet before it is machined. The use of an N/C machined tool is preferred when the part has abrupt changes in contour or is extremely large to ensure accuracy of contour over the entire surface.

For matched-die molding, the demands on the mold are much greater. The molds are subjected to enormous pressure and temperature changes and must be strong enough to move a viscous molding material within the mold. These molds are generally steel.

The mold requirements for vacuum bag molding, especially when an autoclave is used, are less stringent. Typical autoclave molds must be able to withstand temperatures of 250 to 350°F (121 to 177°C) or up to 600°F (315°C) for special applications and the forces caused by thermal expansion. Exceptions are tools with large hollow areas that are not vented to autoclave pressures, such as a box or tube closed on each end. If there are a large number of voids in the autoclave tool, these may expand and cause the tool to degrade rapidly. Therefore, the use of aluminum, composites, metal-coated composites, and a variety of other materials is possible. However, the heating process requires that special consideration be given in the design of molds. The differences in the coefficients of expansion of the part and the mold become much more significant as the size and complexity of the mold increase and as temperatures rise. In the curing of the part, the mold and the part expand together during the initial phases of the cure heat-up. But, at a certain temperature/time relationship, the part gels and becomes hard. From that point on, the part and the mold expand at their own rate depending on their own distinctive coefficient of thermal expansion. After cure, the part and the mold cool at their own rate as well. Consequently, stresses due to this differential in thermal expansion are likely, especially if the part is held within the mold.

In all cases, the choice of whether to use a male or female mold is determined by the part design, the application, and the ease of manufacture. For instance, a radome nose for an aircraft should be made in a female mold because the outside of the finished part must be finely finished for good aerodynamics. On the other hand, an I-beam would be made in a male mold because of the ease of manufacture. Male molds can also be used when serious differences exist between the coefficients of expansion for the mold and the part. Other considerations in the choice of the mold material include heat transfer capability, machinability, useful life, ease of repair, dimensional stability over time, and initial cost.

3.3 METAL TOOLS.

When parts are small or simple in contours such that thermal expansion problems are not critical, aluminum is the metal most commonly used in autoclave molds for composite materials (see figure 16). Aluminum is much lighter than steel, less expensive to machine, and has better conductivity. The face of the mold is machined or bent to coincide with the shape of the part. This face is reinforced by headers, egg crate, or other structural members to insure that the stresses of handling, weight, and expansion can be withstood without affecting part dimensions. The egg crate substructure also helps minimize the heat sink on the back side of the tool. The more openness of this construction allows preferred air flow during cure cycles (see figure 17). Some care should be taken to insure that the face material and the backing are similar alloys in order to reduce any mismatch of thermal expansion of these two mold parts.

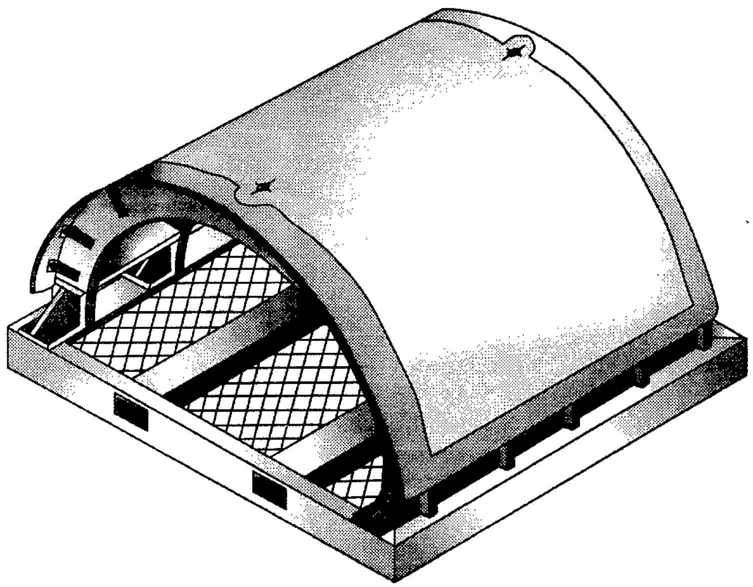


FIGURE 16. METAL LAY-UP MOLD

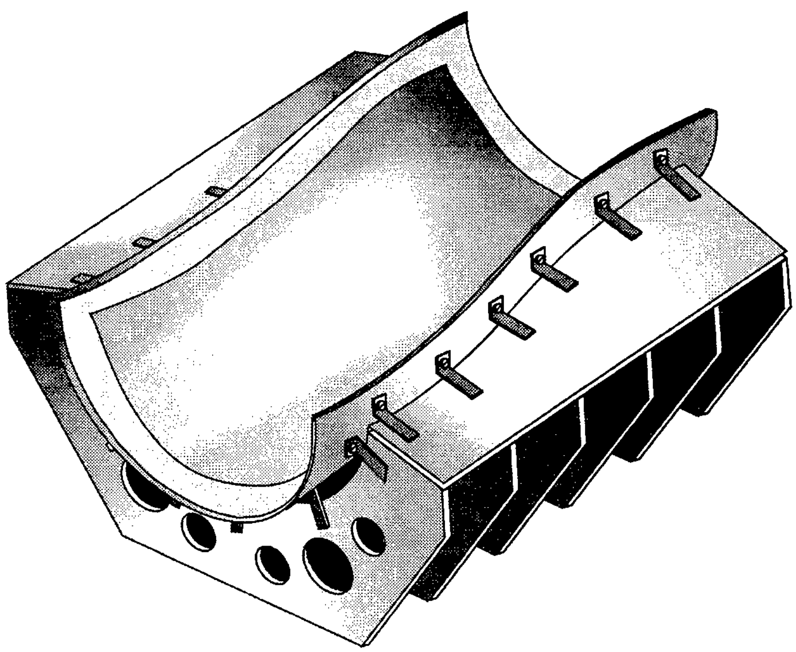


FIGURE 17. NICKEL LAY-UP MOLD

The biggest problem with metal tooling is the substantial difference in the thermal expansion coefficient between metals and composites. Metal typically exhibits three to seven times more expansion than the majority of composites. Steel and Inconel have lower coefficients of thermal expansion than most metals and are often used when high-temperature metal tools are required.

To accommodate the difference in thermal expansion coefficients, the mold may be built to a smaller size than the part. In general, metal tools are more durable and more suitable for production quantities.

3.4 COMPOSITE TOOLS.

The greatest advantage of tools made of composites is that the coefficients of thermal expansion (CTE) of the mold and the part can be made to closely coincide. To accomplish this, the resin and fibers and the fiber orientation should be similar in the part and in the mold.

In practice, the exact matching of CTE is not done because the differences in normal tools and in most parts are minimal relative to other tooling materials. If matching is achieved this greatly reduces or solves the problem of stresses induced by expansion mismatches. This advantage is most significant for large or highly complex parts. Another advantage of tooling made of composite materials is the savings in weight. A typical composite tool is about one-third the weight of a comparable aluminum mold. The cost of composite tooling is also generally lower than metal tooling, as little as half the cost of aluminum tools, depending on complexity.

However, among the disadvantages is that fewer parts can be made although high-temperature resins and experience are now increasing the life expectancy of carbon composite tooling. Both high-temperature epoxies and polyimides are successfully extending the life of composite tools (in some cases to over 500 cycles). The retention of surface finish is also improving due to the use of high-temperature capability prepreg materials or, more recently, a fine surface layer of carbon mat (veil). The tools are cured in an autoclave at 100 psi (690 kPa) to eliminate voids. The prepreg materials provide more uniform laminates, thus significantly reducing resin-rich and resin-poor areas.

The tooling industry, especially the plastic tooling field, have started developing new resin systems which have surface hardnesses equal to or greater than that of aluminum. These resin systems coupled with the very low thermal expansion ratio of woven graphite cloth have provided tools which can be accurately reproduced at relatively low cost when compared to their metal counterparts. These new tools also have very good longevity if they are properly designed, fabricated, used, maintained, and stored.

The most common method of producing composite tools is to start with a model from which a plaster master is taken, make a transfer tool (usually a plastic faced plaster), and produce the finished composite tool which is laid up on the transfer tool and then autoclave cured (see figure 18). The finished tool may be reinforced as required and then used to make molded parts.

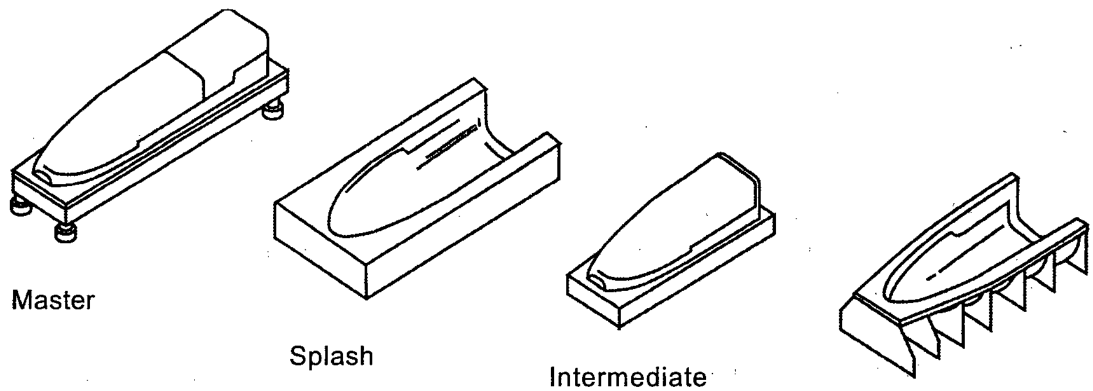


FIGURE 18. FLOW OF COMPOSITE TOOL FABRICATION

3.5 METAL-COATED COMPOSITE TOOLS.

Many of the advantages of both metal tooling materials and composite tooling materials can be combined by coating a composite mold with a metal. The metal affords long life, good mold surfaces, faster heat-up times, ease of repair, and better temperature capabilities; while, the composite offers lighter weight, lower cost, and ease in producing large molds. The critical factor of the coefficient of thermal expansion, while greater than for an all-composite mold and less than for metal, can be highly reproducible. The choice of metal and composite must be made carefully to achieve the best match of thermal expansion.

Metal-coated composite molds are produced through two methods. One method involves fabricating the composite tool and, subsequently, plating it with metal through electrolytic or chemical plating. The metal coating is typically 0.0018 to 0.25 inch (0.04 to 6.4 mm) thick. The other method involves coating the transfer tool metal either by plating or thermal spraying. The composite tool is then fabricated over this metalized surface, and the metal becomes the face of the composite tool. In this method, metal thicknesses are typically 0.060 to 0.125 inch (1.5 to 3 mm). The chief drawback of metal-coated tooling is surface cracking after extended service.

3.6 ELASTOMERIC TOOLS.

These molds are not composed entirely of elastomers but use elastomers in the key areas where special pressure needs to be exerted.

The hollow composite part is placed in a rigid box, which effectively constrains any outward movement of the part. Then, an elastomeric material is placed inside the hollow part. As the assembly is heated, the elastomer expands and presses out against the part to provide the required pressure for consolidation. An important consideration in using this method is the need to know the coefficient of thermal expansion of the elastomer and to carefully control the volume of elastomeric material. Otherwise, very high pressures could be generated (over 1000 psi (6900 kPa)), damaging the part and the tool. This method is called trapped rubber molding.

In this method, the elastomer acts as a pressure pad to provide compression where the bagging material may be limited in movement to better transfer the hydrostatic pressure of the autoclave to the desired location. These elastomeric tooling aids are sometimes called pressure intensifiers.

The major disadvantages of elastomeric molding are the heavy, bulky tooling often required to contain the pressure in trapped rubber molding, the decreased thermal conductivity of the rubber, and heat aging of the rubber.

In hydrostatic forming of thermoplastic composites, elastomeric tools may also be used in molding thermoplastic laminates. One die is usually metal, while the other is elastomeric and either flat (if the part contour is small and simple) or cast to mate with the metal.

3.7 EXPANSION TOOL MOLDING.

Expansion tool molding utilizes rubber inserts in a metal or epoxy tool that expands when heated to provide the molding pressure. The application of expansion tooling is limited to part configurations with deep channels where the rubber tooling can be utilized. The primary advantage of expansion tooling is its ability to fabricate parts without an autoclave.

Expansion tooling is dependent upon materials with high coefficients of thermal expansion. Silicone rubber has a coefficient of thermal expansion that is up to 100 times that of a typical graphite/epoxy tooling material. Expansion tooling is designed to utilize this difference in thermal expansions. The female areas of the mold are made of a material with a low coefficient of thermal expansion. The male plug that fits into the female tool is made of silicone rubber or other rubber-type material. When the tool is heated, the rubber male plugs expand at a much greater rate than the surrounding female tool. Pressures up to 2000 psi can be achieved at 350°F. This pressure acts in a fluid nature in all directions. The molding pressure can be controlled by controlling the temperature, composition, thickness, and the ratio of rubber volume to the female mold volume. Imbedded in the rubber plugs are electrical resistance heaters. The electrical heaters ensure even heating of the tool.

3.8 MATCHED-DIE MOLDS.

Matched-die manufacturing molds are used for compression molding of sheet molding compounds, bulk molding compounds (SMC, BMC), or preforms. The molds required for this process are metal molds that can withstand high pressures and, thus, are most often made of steel.

In the flash-type mold, the amount of material charged into the mold is generally slightly more than the mold capacity. The molds do not meet at the top and, thus, allow the excess material to be squeezed out as a thin flash on the part. This flash is removed after the part is removed from the mold. The second type of mold is similar to the flash-type mold, except that the flash is vertical. The third type of mold is the landed-plunger type, which produces no flash. The male

and female molds mate precisely (landed) and the resulting product needs no trimming. If the charge of material in this type mold is not controlled, short shots (inadequate material which will not fill the mold), excessively thick, or poorly defined parts can result.

All of these mold types may be either cold or integrally heated, depending on the requirements of the particular process, and generally require some provision for the air to escape. This can be done by providing an air vent or by simply opening the mold slightly for a short period just after the initial closing of the mold. Knock-out pins are common in almost all matched-die molds to facilitate the removal of the part.

3.9 CERAMICS.

Ceramics produce favorable characteristics for molds. They have the lowest coefficient of thermal expansion and their thermal conductivity approaches that of some hardened tool steels. However, ceramics are brittle at ambient temperatures. They must be protected from hazards during process handling. One way to afford protection is to enclose ceramic inserts in a steel case.

As a summary, table 5 provides a handy reference of advantages and disadvantages of different tooling materials.

TABLE 5. TOOLING MATERIALS COMPARISON

MATERIAL	ADVANTAGES	DISADVANTAGES
Carbon Fiber/Epoxy	dimensional stability low weight	limited temperature
Fiberglass/Epoxy	good heat-up rate low cost complex shapes low weight	limited durability plaster model required
Aluminum	easily machined relatively low weight good heat-up rate long tool life	high CTE, tools must be designed with springback
Steel	compatible CTE long tool life	machining is slow high tool weight slow heat-up rate
Electroformed Nickel	compatible CTE long tool life good heat-up rate	size limitations cost model required
Bulk Graphite	low CTE high-temperature capability	brittle, easily damaged stock size good heat-up rate limitations
Ceramic	low CTE high-temperature capability low cost	poor heat-up rate brittle, easily damaged

3.10 TOOLING/TOOLING AIDS.

Caul metal or composite plates are used to provide better surface characteristics to the side opposite the mold and to restrict the movement of the part during molding. These are secondary tools to the mold itself. Caul plates are laid on the back of the laminate and follow the general contour of the desired part. Because they are inside the bag, these plates transmit the pressure and impart a smooth finish to the part. A caul plate may also be used to restrict the movement of a part. As the part expands, it meets the caul plate and further expansion is restricted. Any resin leakage is routed sideways.

3.10.1 Plastic-Faced Plasters.

Plastic-faced plasters (PFP) can be used in place of a plaster splash when a more durable and permanent pattern is desired without the expense of having one either machined out of metal or laid up out of fiberglass.

PFP's can be used in place of plaster lay-up patterns when fabricating graphite/epoxy or fiberglass/epoxy lay-up molds to give you a smoother surface and one that has vacuum integrity.

3.10.2 Check Fixtures.

Many tools require a method to check the contour of the tool surface. Typically an inexpensive check tool is used for this contour check function. The check fixture is mated to the bond tool and a feeler gauge is inserted through the access holes to measure the gap between the bond tool surface and the check fixture. Numerically controlled inspection machines can also be used to verify mold surface contours to a high degree of accuracy. Prior to using the bond fixture in production, it should be determined that the fixture when used with the specified materials, lay-up/bagging methods, and cure cycle is capable of producing parts which meet design requirements. Tool inspection is usually a requirement for the FAA processing standards.

3.10.3 Tooling Fixtures and Templates.

In the manufacture of structural composite assemblies, tooling fixtures and templates are the primary media of control used to assure dimensional and contour compliance. Quality assurance engineers inspect and accept these tools as well as tool-proofing articles. Before a tool is used for the fabrication of parts, a complete thermal survey and contour check should be performed. This procedure is referred to as tool proofing.

3.11 MOLD PREPARATIONS.

Mold maintenance is best relegated to specialized personnel, while preparations for the bag molding processes are assigned to production personnel. A successful practice is to provide production personnel with soft tools and solvents that do not degrade the molding surfaces. Methyl ethyl ketone (MEK) is the solvent most often used for cleaning molding surfaces. If the

production tools and solvents are inadequate for removing debris and cleaning, the molds are taken out of service for maintenance, repair, or replacement. After the molds are returned to service, they are solvent-wiped clean and mold release agents are applied.

3.12 RELEASE AGENTS.

The term release agent or parting agent or lubricant is used to describe a wide variety of chemicals which provide a barrier between a mold and the surface of a part being molded. There are two basic types of release agents, internal and external. An internal release agent is an additive which goes directly into the resin formulation. An external release agent is applied to the surface of the mold.

Release agents are important because, while two solid surfaces generally do not adhere to each other, the use of a release agent becomes important when a solid and a liquid or a solid and a paste or dough form an interface and adhere to one another. Some of the factors that influence the adhesion of two materials to each other are penetration, chemical reaction, surface tension, surface configuration, and polarity differences. Release agents have become such an integral part of the manufacturing operation that today there are at least 70 suppliers. Of these, only a few manufacture their own basic ingredients. These are the suppliers who have proprietary resins offering properties that are unique among release agents. Many suppliers merely repackage and offer standard chemicals in the forms of aerosols or bulk shipment.

3.12.1 Properties of Release Agents.

Since the release agent can affect the properties of the part itself as well as the quality of release, proper selection and application are vital to the successful use of release agents. The optimum release agent will prevent damage to the part, provide many releases per application, not build up on the mold or transfer to the part, and will preserve mold detail and design. It will make the production line faster, more economical, and profitable. It will keep the mold in production longer by minimizing mold build-up. While there is still considerable discussion and argument among molders concerning the relative merits of internal versus external release agents, the following factors are those which should be considered in selecting the proper release agent:

- The particular polymer composition with which the release agent is to be used: Will it release and, if so, how easily?
- The process and conditions to which the composition is to be subjected:
  - Will this result in excessive build-up on the mold?
  - Will the release agent be able to tolerate operating conditions?
  - Will the mold stay clean?

- Will the down time be minimal?
- If the mold must be cleaned frequently, will it have any deleterious effect on the mold?
- Will the release agent, be it internal or external, be compatible with the subsequent steps in the operation, such as painting and bonding?
- If an external agent, is there sufficient time on the production line to properly apply the release agent?

• Effect on the final product:
  - If an internal release agent, will it have any undesirable effects on the overall properties?
  - If an external release agent, what type of finish is desired?
  - Are there cosmetic effects to be considered?

• Safety:
  - If an external release agent, what solvents will be used?
  - Is there sufficient ventilation?
  - Are the solvents acceptable?
  - Is there any possibility of skin dermatitis?
  - If an internal agent, will there be constant blooming of the agent resulting in undesirable surface effects?

• Economics:
  - What affect will the price of the release agent have on the unit cost of the part?
  - How does it affect subsequent steps in the operation?
  - Have all associated costs been considered?
  - It is most important when considering the purchase of a release agent to look at the cost per use rather than the basic cost of the item since, in the long run, this is what really counts.

As stated above, it is sometimes possible to choose between an external and an internal release agent. However, in many cases such a choice is not available. As an example, hand lay-up and spray-up operations require an external release agent. On the other hand, SMC, BMC, and premixes which are compression molded in metal dies usually depend on an internal release agent. Many injection molding operations make use of internal release agents and many molders will design molds in such a manner as to avoid the use of either type of release agent. In the early days of the composite industry, the common method of assuring release was to apply waxes to external molding surfaces. With the increasing sophistication of high-speed production operations, however, a faster method was necessary. This has resulted in the development of proprietary multiple release agents such as those manufactured by FreKote, Incorporated; Contour Chemical Company; and Axel Plastics Research Laboratory and the development of specific internal release agents to eliminate the time consuming application of the agents to the die. While silicones are also widely used, they must be handled with care in certain operations because silicones can easily become airborne and, as a result, surface contamination of parts in the immediate vicinity is likely. This surface contamination can affect subsequent steps in the operation such as bonding and painting. These steps are quite critical in the aerospace industry; for example, some aerospace companies will not permit silicones on their property.

3.12.2 External Release Agent.

An external release agent does not destroy the characteristics of the polymer. It is often less expensive than an internal release agent. While there are some who believe that the best external release agent is one that leaves the mold on the surface of the part so as not to contaminate the mold, this is not true. In fact, it is not even desirable because the release agent, by leaving the mold on the surface of the part, is thus contaminating the part. This then requires a subsequent cleaning step and, in many cases, the solvents that would be necessary to remove the release agent may not be compatible with the part. Consequently, in numerous cases, a nontransferring agent such as supplied by FreKote, Inc., is the most desirable type to be used where painting and adhesion are subsequent steps in the manufacturing operation.

Most external release agents can be applied by spraying, brushing, or dipping. Since they are being applied to the surface of the mold, the condition of that mold surface becomes important. The preparation of the mold surface can be a major step in securing a properly coated mold particularly when a change in a release agent is contemplated. Silicone oils are generally removed with toluene or mineral spirits.

On the other hand, waxes must be removed with chlorinated solvents such as methylene chloride, trichloroethylene or perchloroethylene. Mold surfaces should be cleaned of both the polymer and excess release agent and the cleaning method chosen depends upon the material of construction. For example, aluminum molds can be subjected to an acid wash with a material such as formic acid. Steel molds are easily cleaned with an alkaline detergent. Copper molds can be cleaned with an acid-based product such as Copperbrite and nickel molds can be cleaned with a commercially available product such as Spic N' Span. These methods are in addition to the

usual abrasive techniques of using glass beads, sandblasting, lime blasting, or walnut shells. In any case, all traces of oils, waxes, or any other foreign matter must be removed prior to application of the release agent. Once the release agent has been applied, if it is of the proprietary nature, it may require a curing cycle. The optimum film durability and releasing capability are obtained if the manufacturer's directions are followed explicitly.

The number of releases to be obtained will vary with the configuration of the mold and the abrasive nature of the polymer. Reinforced polymers naturally tend to be more abrasive. However, it is not necessary to recoat the entire mold when slight sticking is experienced. The mold surface, even when hot, can be touched up with fresh release agent in the areas where excessive wear has been noted. If the mold surface is hot, one should use a release agent especially designed to be applied at an elevated temperature. There will come a time when the mold must be thoroughly cleaned and it is most prudent to follow the directions of the release agent manufacturer. This will ensure that the cleaned mold surface will be receptive to the application of fresh release agent.

In general, a noncontaminating release agent is preferred for most composite applications and this is especially true for aerospace use where laminating and hand lay-up are predominant. As more efforts are made to raise the operating temperature of composites, greater demand is placed on the release agent. This is especially true, not just for achieving extreme temperature use, but because in most composite applications, especially in aerospace, the mold is usually a plastic reinforced material such as epoxy. If the mold release fails to do its job, the part not only does not release, it usually results in extensive damage to the mold surface as well as the part since the part must then be pried loose and much chipping and gouging results. Here, too, because of the size and shape of the parts, it is not practical to clean the surface of any release agent which has transferred to the part.

In addition to the proprietary release agents, there are a great number of others. Among these are the following:

- Waxes: Here both natural and synthetic waxes find application as release agents. Paraffin and microcrystalline waxes, waxes of vegetable origin, and waxes of animal origin are all used. The synthetic waxes have attained considerable importance; practically all materials from C_{10} and up have found use as release agents.

- Metal Salts: In this category the fatty acid having the widest use is stearic acid. It has a sharply defined melting point and does have good wetting properties. The main derivatives of stearic acid such as the calcium, zinc, and lead salts also serve as release agents. Which metallic stearate is chosen for a specific application will depend primarily on the polymers and the other surfaces. Calcium and lead stearate are the dominant ones. Zinc stearate is substituted for lead where nontoxicity is specified, but is not nearly as stable as lead stearate. In polyvinyl chloride, calcium stearate is probably the most effective. In rubber processing both aluminum and magnesium salts are preferred.

- Polyvinyl alcohol: This material is generally applied as a coating from a water solution in the form of a cast or extruded film.

- Polyamines: These find application only in the form of extruded films since they are mostly insoluble in the commonly used solvents.

- Polyethylene: Polyethylene is used as a film in the processing and shipping of uncurled rubber and many times as a paper laminator in packaging.

- Silicones: The commercially available silicones are all polymeric in order to obtain high boiling points and low volatilities as well as heat resistance and resistance to oxidation. Silicones are applied in the forms of fluids, resins, and greases.

- Fluorocarbons: Fluorocarbon polymers are available in the form of sheets and as dispersions. Tedlar®, polyvinyl fluoride, a DuPont film, usually 0.002 in. (0.051 mm) thick is used extensively as a release agent in autoclave molding operations.

- Inorganic compounds: These are probably the oldest release agents known. Because of their insolubility they are used strictly in the form of powders which exert their release properties because of their flake-like crystal structure. The most important members of this class are talcum and mica. They are usually applied as a fine powder sprayed or dusted onto a surface. In many cases they can be blended with metal stearates to improve the release action.

3.12.3 Internal Release Agents.

Among the many advantages of internal release agents are the elimination of application, a wipe down, and scrubbing of the mold, as well as elimination of vapors. In some cases, internal agents actually improve the impact strength of rigid polymers; therefore, where appropriate, internal release agents can be very economical. However, as stated earlier, care must be taken with the use of internal release agents to guarantee that they have no adverse affect on physical properties or any other specifications. In particular, internal release agents are used in pultrusion processes where pulling of the part through the mold would tend to wear off an external release.

In summary, regardless of whether one chooses an internal or an external release agent, certain key factors should be considered in making the choice. Certainly an external agent is called for if one is working with a polymer having very narrowly defined specifications. While ease of release is certainly the first major factor to be considered, all the other factors mentioned earlier must be taken into consideration. Cost, while sometimes considered to be a factor, is really not all that important. If the release agent works, gives you efficiency of production, and has minimal affect on other related costs and subsequent processing operations, then the cost of the release agent is usually insignificant with respect to the overall cost of the product. In general, external release

agents are more readily available, more widely applicable, and certainly easier to use and, for composite applications, are probably the release agent of choice.

3.12.4 Release Film Plastic.

Release films are used on tool surfaces and over bond lines to prevent adhesive bonding by the flash that escapes under pressure during the adhesive cure cycle. The recommended types are listed below:

- Fluorinated ethylene propylene (FEP) or TFE (0.0015 or 0.002 in. thick)
- Teflon, permeable or nonpermeable (0.0015 or 0.002 in. thick)
- Modified halocarbon (TFE), solid or perforated (E3760, 0.0015 or 0.002 in. thick)
- Coated (PVA) fiberglass peel ply, nylon style (18301-F58)
- Dacron peel ply

3.12.5 Solvents.

Solvents are used for the hand cleaning of tools and details before and after the curing operation. The more important cleaning solvents are methyl ethyl ketone, methyl isobutyl ketone, toluene, acetone, and alcohol.

4. PARTS.

4.1 INTRODUCTION.

Composites, particularly carbon/epoxy (C/Ep) offers the potential for major weight savings in aircraft design. This material has high strength-to-weight ratios for both tension and compression loads which are approximately 30% higher than aluminum. Thus, weight reductions of 20% or better are common when replacing aluminum structure with C/Ep composite structure.

A disadvantage with composite structure is the relative high cost of raw material. It is therefore imperative that the designer carefully evaluate the manufacturing operations and seek to minimize the cost to build, inspect, and repair components.

4.2 GENERAL PART FABRICATION.

Before part fabrication, the mechanic must have the proper tools, the raw materials, and the green light from Quality Assurance to proceed. The tooling must be certified for use in fabrication. The tooling can be either a male or a female mold. The mold needs to be properly prepared with a release agent, normally in the form of a parting wax or a liquid parting film, such as Frekote or other commercially available items. The tool should be checked to see that it is the correct tool for the part, that the tool is dimensionally correct, and is currently certified for use with the latest engineering changes.

The tool is inspected for surface imperfections such as cuts and scratches. Once the tool has been selected the preparation will include a physical clean up and an application of parting liquid that will allow the mechanic to remove the part once it has been cured. In many instances the first application of parting agent on the tool requires a bake cycle, normally in the 250°F range for 1 hour. If there will be some period of time between the preparation of the tool and the use of the tool, the tool should be put in an environmentally dust-free area and/or protected with some type of covering. A clean lint-free cloth should be used. At the time of use, preparation of the tool is completed. The lay-up process consists of selecting raw materials that have been checked to see that they are in compliance with the specification and that they are the correct materials for use in that part. This information is indicated on the shop traveler. The material lot and batch number should be noted for traceability.

Once the material has been selected, the mechanic familiarizes himself with the ply orientation that might be called out on the engineering drawing or fabrication procedure. He also needs to be aware that certain materials, especially some of the epoxies may cause skin irritation; therefore, he should wear gloves or some type of noncontaminating surface cream on his hands before he starts the lay-up procedure. (Refer to applicable Material Safety Data Sheets (MSDS) for proper preproduction evaluation (PPE) and handling requirements.) Depending upon what the part configuration is, the mechanic may have to obtain his materials individually by cutting them from rolls of stock material or obtaining resins and mixing them to the required mix ratios in order

for them to cure alternatively. Materials for the hand lay-up process may be pre-kitted, in which case the mechanic will need to insure that the proper kit is obtained for that particular part. One precaution that the mechanic must take is that in the event the materials have been kept in cold storage, he needs to assure that they are warmed up to room temperature prior to their application into the part and that there is no evidence of moisture on the materials, especially on the preimpregnated fabrics that may be inadvertently put into the part.

4.3 LAMINATE LAY-UP DEFINITION.

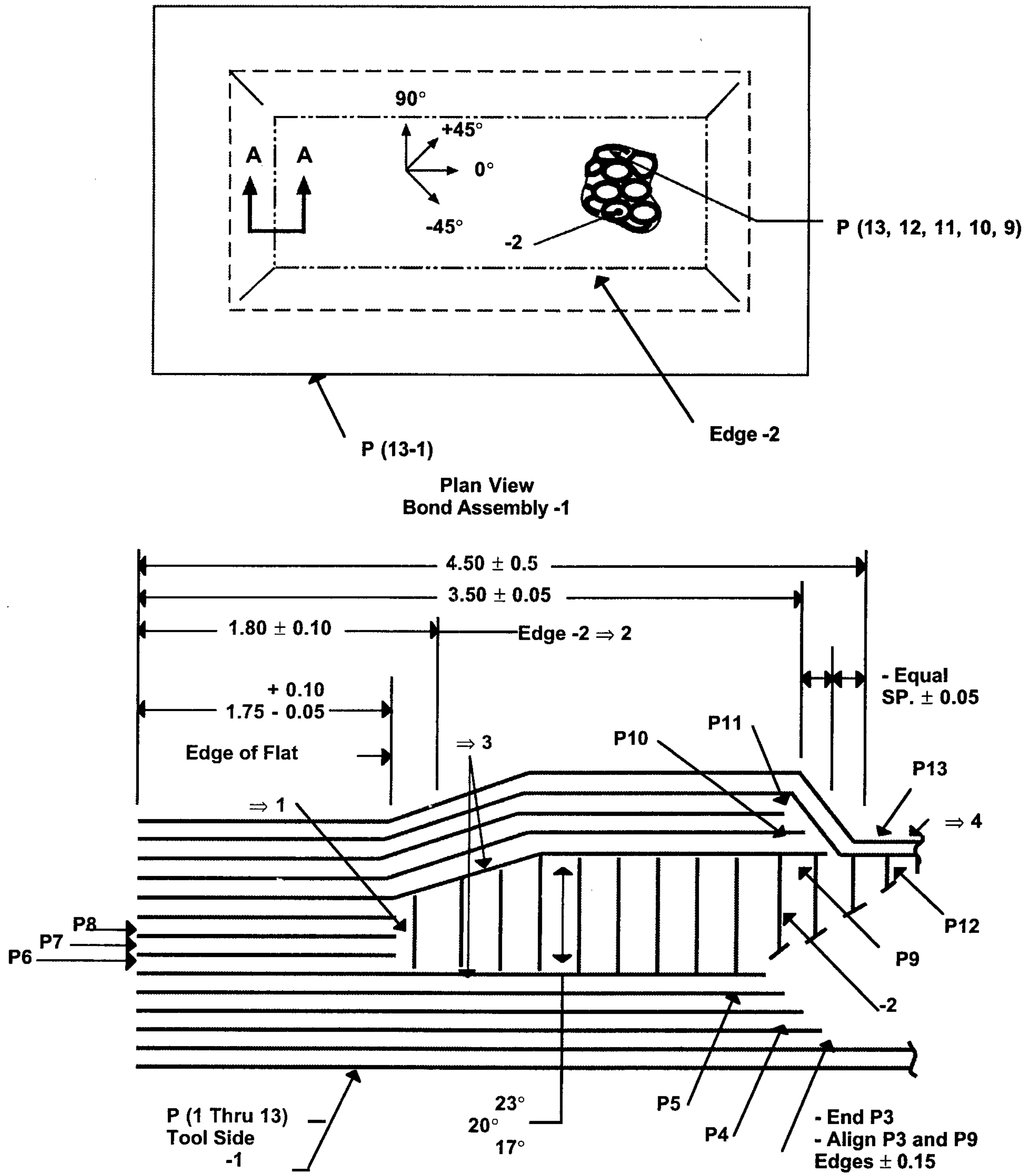
A structural laminate is designed to have a specific lay-up, or ply arrangement, based on the various design criteria imposed on it. A laminate definition code has been established by the United States Air Force to ensure a one-to-one relationship between the actual ply arrangement or laminate stacking sequence and the laminate definition. Each company, however, has its own drawing callout code, a typical one being shown in figure 19.

Orientation of plies is the most important part of laminating. Improper placement of plies will effect structural property of a part, and is cause for rejection. The blue print will show proper orientation and placement of plies. Some molds will indicate warp direction. For example, the warp direction of woven material is the direction in which material is unrolled. Using continuous fiber material, linear direction of fiber is considered 0°.

A laminate lay-up definition refers to the fiber orientations of successive plies in the laminate, with respect to an established reference coordinate system. For example, in an aircraft wing skin lay-up, the reference X direction may be assumed to be in the spanwise direction, along a mid-spar centerline. Figure 20 presents the conventions for the definition of a ply orientation and the ply numbering sequence, a sample laminate lay-up, and a schematic of the cured laminate. This laminate can be defined using any of the following expressions:

- $0/-45/90/+45/0/+45/90/-45/0$
- $\left(0/-45/90/+45/\overline{0}\right)_S$
- 11-ply, 33/44/23

The first two expressions give a complete ply sequence in the total laminate lay-up. The second expression takes advantage of the midplane symmetry in the laminate lay-up. The third expression offers condensed definitions of the number of plies at every orientation where the numbers represent percentages of total laminate in a given ply direction.



⇒ 1 Filler plies P (6, 7, 8) to be butted to core edge with an overlap of 0.00 to 0.20 to provide a smooth transition from area to core ramp.

⇒ 2 Acceptable limits for edge of core.

⇒ 3 Bond plies to core with BMS 8-245 adhesive and cocure per BAC 5562.

⇒ 4 Apply one layer of Tedlar film (PVF) transparent 100BG 30 TR per BAC 5562 on the outer surface of the non-tool side face sheet.

FIGURE 19. SAMPLE CALLOUT

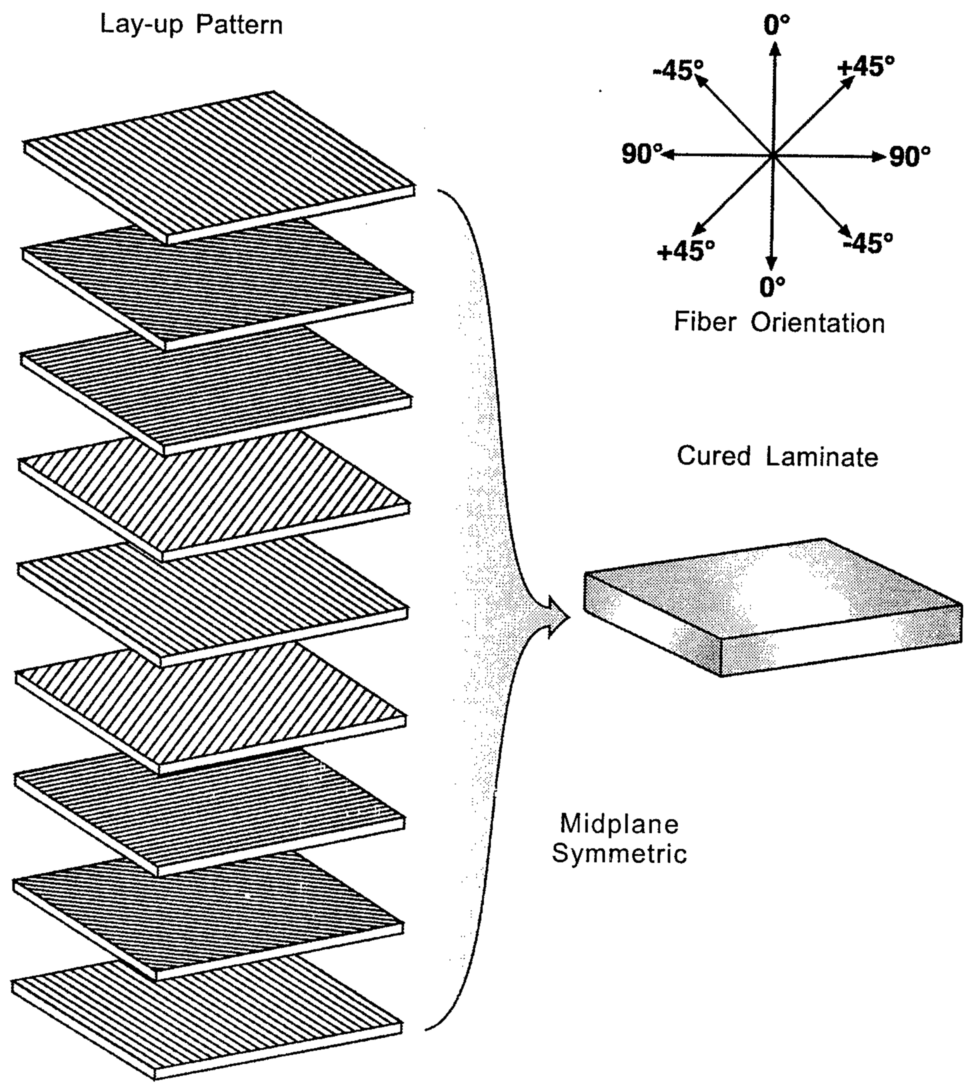


FIGURE 20. LAMINATE ORIENTATION

4.4 LAMINATE FABRICATION.

Structural laminated parts may be fabricated using many different processes. Most of the aircraft structural laminates are currently being fabricated using prepreg forms. Prepregs are initially cut and laid up in a clean room to obtain the geometry and ply arrangement of the laminated part. They are debulked, if required, during the lay-up and subsequently bagged. The bagged lay-up is placed into an autoclave to cure the laminate under conditions specified in the process specifications. The reader should refer to sections 5 and 6 of this report for additional details on the fabrication process and for a description of other manufacturing methods.

Once a lay-up process has started with the first ply in place, check for ply orientation, positioning on the tool, and that the material is worked into the tool's contours. In the case of a prepreg, ensure all air bubbles are worked out by use of a plastic squeegee or hand working. In

the case of prepreg lay-ups, it is possible to put down several plies, continually working one into the other to remove any air entrapment or wrinkles into the part, but at some point it is advisable to debulk. This process places a vacuum bag over the plies that have been laid down at that particular point and draws a vacuum on the stack to remove any air and to compact the ply build-up.

If the part is made by using preimpregnated fabric or prepregs that have several plies, it may be advisable to use a debulk cycle to help remove the air or trapped gases in between the laminates. This is done by applying a vacuum bag to the laminate at its particular construction stage and simply pull a vacuum down and hold the laminate under a vacuum for a period of 20-30 minutes. Low heat <150°F can also be used here. This will help compact the laminate as well as remove any air that may be trapped into it. Once a debulk cycle has been completed, the laminate sequence lay-up can be continued using the same parameters that we discussed earlier. At such time as the laminate is totally complete, the mechanic will apply the final vacuum bag for the cure process. Pressure and heat are used to complete the laminate.

The mechanic will apply the final vacuum bag for the cure process. In the case of autoclave curing, special precautions must be taken to insure vacuum integrity throughout the curing process. A leak check should be performed as per the process specifications on the blue print or accompanying shop traveler. This simple process involves the placement of a vacuum gage on the final vacuum bag while under vacuum to measure any vacuum loss when the supply hose is disconnected. A reasonable vacuum loss rate is in the 1-3 inches per minute range depending on specific processing specifications. If the loss rate is unacceptable, the vacuum bag must be repaired or replaced prior to cure processing. Any slight hole or tear in the vacuum bag can result in a blown bag during autoclave processing. The outcome of a blown-bag situation (perforation in the vacuum bag leading to a loss of pressure during cure) is almost always scraping the part. Therefore, all precautions must be taken to eliminate any potential for leakage prior to leading parts into the autoclave or oven for cure processing.

Placement of any thermocouple (TC) wires are also critical at this stage. TC wire readings need to be verified as well as the seal around the thermocouple within the vacuum bag. Proper TC placement with the vacuum bag is critical for consistent measurement and accuracy throughout the cure. Known cold or hot spots on the mold, TC wire placement within the bag, and overall varying tooling geometry can produce undesirable temperature readings during the cure. For this reason, TC placement within the tool should be given appropriate consideration for optimum air-flow temperature readings during the cure.

Following the vacuum bag integrity verification, any pleats or dog ears must be fastened down onto the bag or tool so as not to impart a mark on the tool during cure processing. Substantial velocities occur within the autoclave during cure processing and can dislodge a pleat or dog ear that has not been taped down properly. A measure of care must be taken when taping the ears down so as not to disrupt the vacuum bag-tool seal.

After these precure issues have been addressed, operators should then place any tooling or part into the autoclave to maximize the airflow in and around the tooling. Loading arrangements should be thought out in advance. Stacking and nesting of the tooling is always a compromise between economics and airflow efficiency. Typically, from an economic point of view, the autoclave should be packed with parts requiring curing so as to minimize per part costs. However, this can have significant consequences to the overall performance of the autoclave curing due to disruption or lack of airflow in and around the tooling. If an operator is not sure of airflow impact, a simple test to verify airflow can be done prior to processing by loading the autoclave and attaching tufts of yarn to different tooling and turning the autoclave fan on. These methods and precautions must be employed for an uneventful autoclave cure and correspondingly successful part manufacturing process.

4.5 PRODUCTION PREPREG LAY-UP TECHNIQUES.

It is essential that prepregs for structural applications be staged to desirable tack and drape qualities. Tack should be adequate to adhere the prepreg to the prepared molding surface or to preceding plies for the lay-up with the application of light pressure. Tack should also be sufficiently light to allow the prepreg to part from the backing without loss of resin. Drape is sufficiently soft to permit the prepreg to conform to the contour of the molding surface. The desirable combination of manageable tack and drape is best attained by woven satin fabric-reinforced prepregs. Nonwoven collimated fiber reinforcements have low strength transverse to the fibers and boron fiber prepregs and stiff in the fiber direction. Sometimes, multi-plied or cross-plied prepregs are used to provide the transverse strengths for lay-ups of broad goods.

To ensure that the cured laminates will not be deficient in durability and required engineering properties, the tack and drape properties of prepregs are modified to suit mechanized equipment or local fabricating conditions. Ideally, temperature and humidity sensitivities are minimized in air conditioned and pressurized clean rooms. The pressure for clean rooms is maintained by filtered air kept at positive gauge pressure by blowers. The pressure is just high enough to prevent airborne contaminants in the surrounding atmosphere from entering the clean room. Usually, the ideal conditions are not achieved and it is often necessary to require seasonal adjustments to the handling characteristics for the prepreg.

In the lay-up of woven fabric prepregs, the drape characteristics of prepregs containing long shaft satin reinforcements are the most compliant. Prepregs with crowfoot satin weave attain less drape, while prepregs containing square weave or basket weave fabrics attain the least drape.

Woven fabric prepregs may be darted to comply to convoluted shapes of low stressed items. Darting is the practice of slitting the prepregs at locations where folds would normally occur in a lay-up. The excess material at those locations may be removed completely and the remaining edges butted together or the prepreg may be slit where a crease in the wrinkle would normally form. The excess material may overlap provided that it is wrinkle-free. When the former method is used, an additional ply is required to compensate for the weak butt joints in the lay-up.

Darting is not recommended for the highly stressed lightweight constructions. On those occasions, prepregs should be cut to predetermined patterns in which joints do not coincide in any of the successive plies. The overlapping joints must be deliberately placed and joint widths must be controlled. Usually, patterns for pre-cutting the prepregs allow for 0.5-in. (1.3-cm) overlaps on the lay-up.

When woven fabric reinforcements are laid up on convoluted shapes, weave patterns become distorted and the fibers change directions. Orientations, on the order of (0°, ±60°) or (0°, ±45°, 90°) are used to compensate for undetermined deficiencies. These plying sequences provide laminates that are quasi-isotropic in properties. However, ply alignments of heavily draped lay-ups of fiberglass-reinforced prepregs are difficult to control. Colored tracer fibers woven into the fabrics simplify the lay-ups and inspections of the composites.

The Burlington Industrial Products Division supplies fiberglass fabric reinforcements with brown warp tracer fibers spaced at 5-inch (12.8-cm) intervals. The J. P. Stevens Company supplies similar reinforcements with blue tracer fibers at 3-inch (7.6-cm) intervals. The tracers show through unpigmented epoxies and polyesters. The adequacies of the orientations and the ply count in a lay-up can be optically verified. Sometimes, fibers that are opaque to X-ray transmissions are included among the warp fibers of custom woven fabrics.

Structural composites must be designed to obtain reproducible properties. The shapes should permit the plies to be oriented in predetermined directions. The principles for the lay-up techniques are similar, whether the lay-up is produced manually or is automated. When the structural shapes permit, the most reproducible properties are developed by laying up plies that are cut to size and then applied to the transfer films. These transfer films or Mylar templates are indexed with respect to specified ply locations and orientations with respect to the mold. Plies that are laid up on templates are transferred to the molds without additional distortions, and the templates are removed after the plies are laid up and transferred onto the mold. Anisotropies of fabric-reinforced prepreg in one ply are corrected with equal but opposite anisotropy in adjacent plies. The corrections to achieve symmetry are important to avoid distortions to the cured laminates. Other corrections are sometimes made by cross-plying compensating misalignments to attain orthotropic properties.

4.6 THERMOPLASTIC PREPREG LAY-UPS.

Although they are stiff and dry at room temperature, thermoplastic prepregs can be thermoformed above their glass transition temperatures and fused after only a short dwell at their melting temperatures. They may be stored indefinitely at room temperature without the need for special precautions. They are not subject to moisture degradations of the same magnitudes as are the thermosetting resin matrices. Currently, the prepregs contain no allowances for resin bleed-outs. Plies are separately thermoformed at about 400°F (204°C), cooled to room temperature, and stacked on the mold to form the lay-up. The lay-up is then vacuum bag or autoclave molded

at about 600°F (315°C). The dwell at fusion temperature depends on the lay-up thickness. A dwell less than 30 minutes is required to fuse an eight-ply graphite fiber-reinforced laminate. Impediments to successful fusion are degraded prepreg surfaces, contaminants, and nonuniform fusion conditions. Surface contaminations result in delaminations and increased voids. Collimated fiber reinforced prepregs comply to curved shapes more readily. Other candidate thermoplastic matrices include polyarylsulfone, polyethersulfone, and acrylic.

4.7 SANDWICH PANEL CONSTRUCTION.

A structural sandwich consists of skin panels, a core material, and adhesives to join them together. The concept behind sandwich construction is that the skins carry bending loads and the cores carry shear/compressive loads. In both cases, the adhesive must be capable of withstanding the forces so that sandwich separation does not occur.

The effectiveness of the sandwich construction is exemplified where by doubling the core thickness, stiffness is increased over seven times with only a 3% increase in weight. When the thickness is quadrupled, the stiffness increases 39 times with only a 6% increase in weight. Sandwich construction gives the highest stiffness to weight ratio of any structural design.

Because of the weight and stiffness advantages of sandwich construction, many uses have been developed, including the following: military and commercial airplanes, helicopters, space vehicles, cargo containers, movable shelters, navy ship interiors, snow skis, and walls for recreational vehicles.

In composite sandwiches, the skins are composite panels. Other skin materials can include aluminum or other metals or plastic sheets. Skin panels are typically chosen on the basis of weight, strength, cost and ease of manufacture. Hybrid skins, such as carbon fabric with aramid fabric on the surface, are sometimes used for special properties such as toughness.

The adhesives are chosen to give strength, temperature compatibility, and for the ability to form a fillet at the cell wall or in some other way to form a good bond with the minimal surface area of the end of some of the core materials. Good toughness and strength are key properties of a fillet. The adhesive material must have a high-melt viscosity and a high surface tension so that the adhesive will adhere in the fillet area and not run down to the flat portion of the part and puddle. A cross section of a typical sandwich with close out is shown in figure 21.

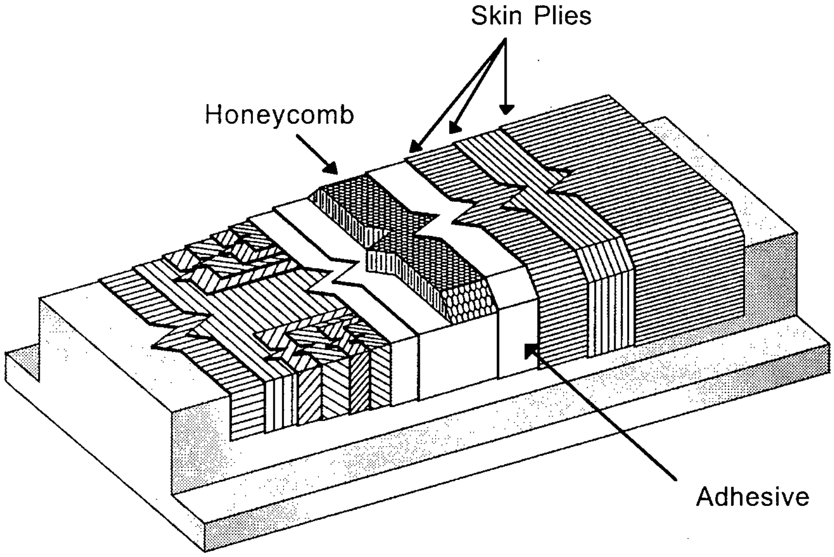


FIGURE 21. TYPICAL SANDWICH PANEL LAY-UP

Two methods of bonding advanced composite facings to core materials are used in fabricating sandwich structures. The first involves a two-step operation in which the skins are laid up and cured independently before bonding to the core material (see figure 22). The second method is a one-step or cocuring method in which the skins are laid up and applied to the core in the B staged condition. In this case, the sandwich assembly is then cured and bonded in one autoclave operation. As new manufacturing methods and techniques were investigated, it was found that quality sandwich panels could be fabricated by cocuring, while achieving equal structural integrity and considerable savings.

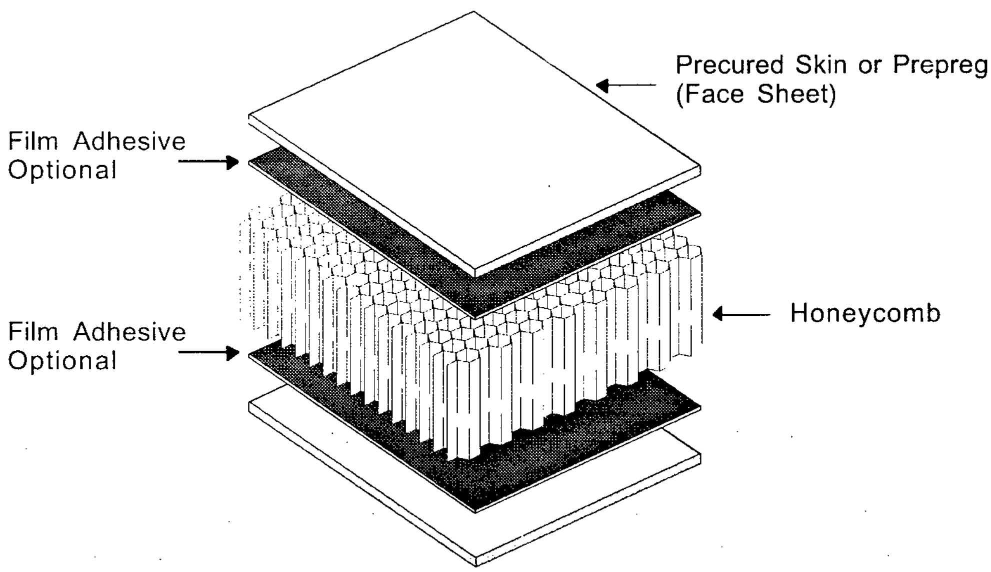


FIGURE 22. SANDWICH PANEL

In special cases of complex core machining and forming, it may be desirable in either of the above methods to bond only one face sheet at a time. For example, to machine one side of the core and bond the skin to the core in a formed mold and then to machine the other side of the core in the restrained position and cocure the second face sheet. Panels are manufactured by the vacuum/autoclave process, lay-up, and bagging techniques.

In the cocuring method, skins may be laminated from adhesive type prepregs made from a modified resin system used for adhesive bonding in which resin content and flow of the prepreg material are such that a uniform filleted bond between skins and core is obtained. However, strength properties of the laminate are somewhat lower when the modified adhesive resin systems are used because of lower pressure cure.

To prevent damage to the core and facing in the cocure method, the total molding pressure is normally not in excess of 50 psi (233, 5 kg / m^2) as opposed to 90 psi for normal laminate curing. Cure and post-cure temperatures are also limited to avoid degradation of the core. Fiberglass facings on graphite skins are recommended to prevent corrosion of aluminum honeycomb core.

4.7.1 Adhesive Materials in Sandwich Panels.

The adhesive must rigidly attach the skins to the core material in order for loads to be transmitted from one skin to the other and to permit the structure to fulfill all the structural requirements. A low modulus or rubber cement type adhesive is therefore never used in a sandwich structure intended to carry substantial loads. The adhesives which are satisfactory for this application are all high-modulus, high-strength materials available as liquids, pastes, dry, or supported films. Any material contemplated for use as a core-to-facing bond should generally meet or approximate the requirements of MIL-A-25463. Adhesives also come in a wide range of toughness or peel strength. As a general rule, a low peel strength, or relatively brittle adhesive should never be used with very light sandwich structures which may be subjected to abuse or damage in storage, handling, or service.

Adhesives, as they apply to sandwich structures, are a somewhat different family of materials than are similar materials required to bond an open cellular core to a stiff and continuous skins. Although these differences are less important with some of the newer modified epoxy materials, they remain basic and must be understood by the designer and fabricator in order to avoid problems. Some factors which merit attention are the following.

- Fillet Forming. In order to achieve a good attachment to an open cell core, such as honeycomb, the adhesive must have a unique combination of surface wetting and controlled flow during early stages of cure. This controlled flow prevents the adhesive from flowing down the cell wall and leaving a low-strength top skin attachment and an over-weight bottom skin attachment. Typical fillets are shown in figure 23.

- Bond Line Control. It is the capability of the adhesive to resist being squeezed out from between faying surfaces when excessive pressure is applied during cure to a local area of the part. Many adhesives are formulated to achieve good core filleting and are subsequently given controlled flow by adding an open weave cloth or fibrous web cast within a thicker film of adhesive. This scrim cloth then prevents the faying surfaces from squeezing out all the adhesive which would result in an area of low bond strength.

- Toughness. The word toughness has many meanings in the world of adhesives. Usually it refers to the resistance shown by the adhesive to bond line crack growth under impact loading. In the area of sandwich core-to-skin bonds, it refers to the resistance shown by the adhesive towards loads which act to separate the facings from the core under either static or dynamic conditions. It has been found from experience that greater toughness in the bond line usually equates to greater durability and thus to longer service life.

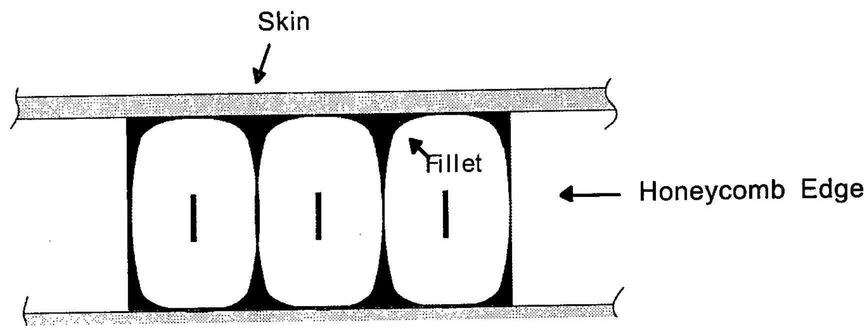


FIGURE 23. HONEYCOMB FILLETS

Many types of tests, for example flatwise tension and beam tests, have been devised to measure toughness, but the most common one used for sandwich structures is the climbing drum peel test, which has the virtue of being easily duplicated as well as possessing an obvious relationship to the toughness whose value is sought. Values of peel strength will vary considerably, depending upon:

- strength of facing
- toughness of the adhesive
- amount of adhesive used
- density of the core
- cell size of the core
- direction of peel (with or across ribbon direction)
- adequacy of surface preparation
- degradation of the adhered surface subsequent to bonding

Because these variables can lead to widely differing peel strength for the very same adhesives, all of them must be properly understood and controlled if the peel test is to be used and its value compared to other test results.

4.7.2 Core Densification.

In some applications, honeycomb cores are densified with lightweight materials, such as syntactic foams.

Syntactic foam materials are used

- to provide a filler material for edge filling, potting of inserts, and compression blocks in sandwich panels.

- to provide a filleting material and for molding contoured compression spaces.

- to provide a core material for structural sections and built-up bearing pads on reinforced plastic parts.

There are two classes of syntactic foam filler material based on usage temperature.

- For temperature requirements not exceeding 250°F, syntactic foam is composed of epoxy/phenolic microballoon.

- For temperature requirement not exceeding 350°F, epoxy/glass spheres are used.

Specific types being used are noted on blueprints, operation sheets, and plastic molds.
Core splice adhesives are also used for core densification or local honeycomb reinforcement. This material is light-gray sheet type adhesive available in 0.025 and 0.050 weight. This adhesive is a foaming type that will expand to 1.7 to 3.0 times its initial thickness. The core splice material is manufactured to specific requirements; e.g., thickness, tack, composition, controlled expansion, compression and tensile strength, and color. The core splice material acts as a fastening method to bond core to spars, fittings, and end ribs, as well as core-to-core bonds. Core splice adhesive is available in 250 and 350°F cure temperatures that are compatible with the adhesive system being used. In rare cases, core splicing can be accomplished with other types of adhesive pastes or films.

4.7.3 Application of Film (Tape) Adhesive.

The different kinds of film adhesive are all applied in much the same manner. When an adhesive has a protective film on both sides, the protective film on one side is removed before applying the film, and the protective film on the second side is removed just prior to assembly. When a film adhesive has only one protective film, the protective film is left on the detail until it is ready for assembly. Adhesive film is placed on one or the other interface of each bond joint. The film is then pressed firmly in place and carefully smoothed out. Some films require heat tacking to hold them in place. Finally, the excess film is carefully trimmed off.

4.7.4 Curing of Honeycomb Assemblies.

Honeycomb assemblies may be assembled and held under vacuum pressure but vacuum shall be vented to atmosphere when the positive pressure reaches 15 psi and prior to the bond line temperature reaching 150°F. Pressure for honeycomb bonding will vary with the type of honeycomb and the type of assembly. In general, unlike composite laminates, honeycomb panels cure with a maximum pressure of 45 psi. The reason for venting vacuum is to stop film or foaming adhesives from being pulled up into honeycomb cells.

Unlike laminated edge honeycomb core panels that require only one cure cycle, trailing-edge panels presently require multiple-cure cycles. The first cycle bonds the lower skin, the leading-edge spar, and the honeycomb core into a subassembly. The details (with adhesive applied) are assembled in a bonding tool that holds them in the proper position for curing. After curing in an autoclave or electric oven, the cured subassembly is carefully removed from the bonding tool and located on a vacuum chuck. The chuck holds the subassembly in the correct position for machining the unbonded upper portion of the honeycomb core to the necessary net contour. The bond cure cycle sheet will give specific pressure and temperature requirements and also the length of time required for bond assemblies.

4.7.5 Fitting, Closeouts, and Fastening of Honeycomb Materials.

Perhaps the most troublesome and potentially critical part of using sandwich materials is the proper fitting of the part and closeout of the edge. The closeout is a cap or finished part that covers the exposed edge of the core material. Closeouts can be added after fabrication or, because most sandwich panels are cured together, the closeout can be added before curing and cocured with the rest of the sandwich structure.

When a fitting or fastener is to be put into a sandwich material, a doubler is often used. Doublers are facing reinforcement added to the sandwich structure in areas of high stress. The doubler spreads the stress over a much wider area. Just like closeouts, doublers can be added after the panel is cured or can be cocured with the panel. Doublers can be internal or external but should be fabricated to give the most gradual spread of stress possible. Core is also densified before installing the fasteners through honeycomb.

Fasteners can also be added to the already cured laminate. In this case, usually the grommet type is used or can be cocured. The grommet type weighs less than the molded-in type but is not as secure.

4.8 ADHESIVE BONDING.

In its simplest form, a bonded structure exists when any two pieces of material are joined together and they achieve their carry-over strength through a chemical rather than a mechanical

bond. This term chemical comprises a wide range of terms as we consider the various resins and adhesives used in modern aircraft construction.

Bonded structure, as we think of it in aircraft construction, is normally of a laminated construction using thermosetting resins. One of the more popular forms of bonded structure is honeycomb in which a core material made of thin metal foil, plastic, or fiberglass cloth in a cellular structure is covered with skins of fiberglass or sheet metal.

4.8.1 General.

Adhesive bonding is increasingly gaining acceptance as a method of fastening details into an assembly. Although bonding or gluing is an ancient art, the animal, fish, and vegetable glues that have been used since recorded history could carry very little, if any, load. Since 1920, when they first were synthesized, organic polymers have greatly increased the selection of raw material available for adhesives. By varying resins, elastomers, fillers, or catalysts, a wide range of materials with high strength, flexibility, and environmental resistance can be produced.

The use of load-bearing adhesives was pioneered by the aircraft industry because of the advantages bonded joints have over other methods of fastening. Metal-to-metal adhesives are chiefly used in thin-metal lap joints in place of rivets and spot welds. Structural adhesives are also used extensively for joining thin metal skins to honeycomb core in the manufacture of sandwich panels. Other fastening methods for joining sandwich panels are not as practical as bonding. Adhesives produce continuous bonds and thus distribute stress loads evenly over the entire joined area.

Properties inherent in polymeric adhesives provide joints capable of outstanding performance under cyclic loading. Adhesive materials are not subject to the same kind of progressive fatigue failures that metals are. In addition, adhesive bonded joints eliminate gaps, bulges, and protruding fasteners that produce drag on aircraft surfaces. The sealing and insulating properties of structural adhesives permit bonding of dissimilar metals with a minimum of bimetallic corrosion.

As a design characteristic, adhesives are important in sonic dampening and fatigue life. Like any structural material, adhesives have both their limitation and optimum service environment. The superior strength of an adhesive-bonded joint lies in its large bonded or fastened area. In order to obtain this performance, adhesive joints must be stressed as evenly as possible; therefore, adhesive joints are very directional. They are outstanding in shear, adequate in tension, but poor in peel and cleavage stresses where the instantaneous stress affects only a relatively small bond area. Subsequently, bonded joints are designed to be loaded in shear tension or shear compression.

Production techniques and equipment for adhesive bonding are much more elaborate than those for conventional fastening. Jigs and fixtures must be designed to ensure intimate contact of the substrates over the entire surface and to provide sufficient heat during the assembly and cure of

adhesive joints. Since bonding is purely a surface phenomenon, surface preparation is more exacting than for mechanical fasteners. In general, adhesives function more effectively in thin sections. As these sections become thicker, the adhesive-to-metal strength ratio is lowered.

Researchers and designers continually find new uses for adhesive bonding. Structural adhesive bonding is used extensively on aircraft. The assemblies listed in table 6 are typical of those produced by structural bonding.

TABLE 6. TYPICAL PARTS PRODUCED BY STRUCTURAL BONDING

Ailerons	Rudders and Elevators
Body Skins	Trailing Edges
Cover Panels	Tabs
Flaps	Wing Panels
Floors	Leading Edges
Landing Gear Doors	Horizontal Stabilizer Panels
Landing Gear Beams	Vertical Stabilizer Panels

Bonding offers a number of advantages that conventional methods of fastening do not provide. The most important advantages of structural adhesive bonding are:

- High strength-to-weight ratio—Bonded panels can withstand greater shearing forces than spot welded or riveted panels and the fewer the rivets, the lighter the plane.

- Superior fatigue characteristics—Metal fatigue is reduced when metal assemblies are bonded. Bonded structures last longer under the greater stress of high speeds.

- Aerodynamically smooth surfaces—Protruding fasteners (rivets) cause air resistance instead of letting the air pass smoothly over the surface. Smoothness reduces friction drag, thus increasing speed.

- Sonic dampening—Bonded structures can better withstand the stresses built up by sonic vibrations. Bonding certain assemblies also helps to reduce noise, thus adding to passenger comfort.

4.8.2 Cleaning and Surface Preparation.

One of the most important steps in obtaining an adhesive bond of high quality is the proper cleaning and surface preparation of each detail. If the surface is contaminated with oil, grease, or other foreign substances, the adhesive will not stick to the metal, and a bond failure will occur. Cleaning and surface preparation must be accomplished according to the process specification. The water break test, figure 24, is used to measure cleanliness of surface.

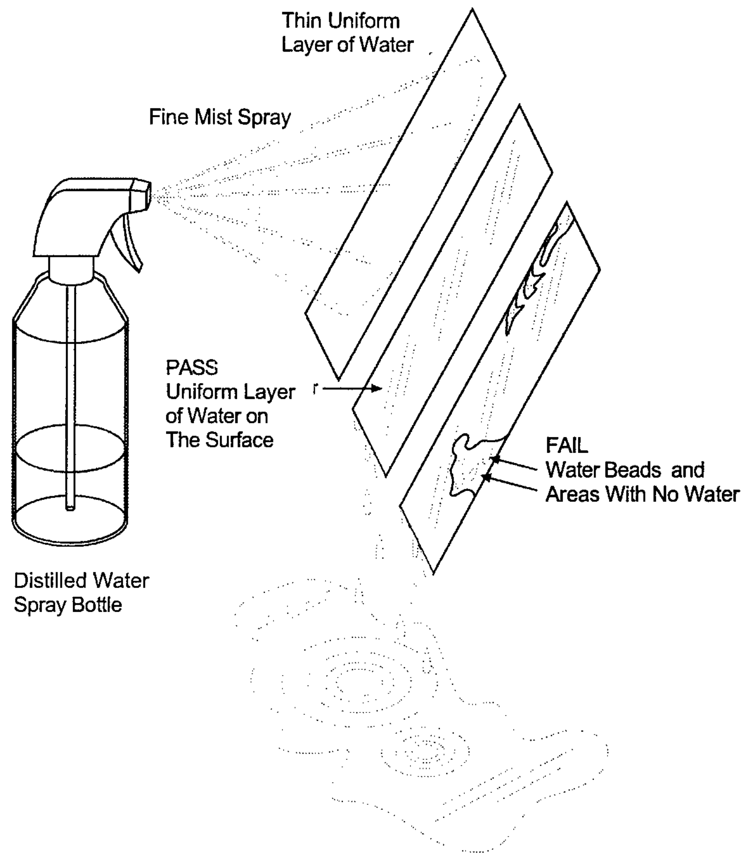


FIGURE 24. WATER BREAK TEST

The cleaning and surface preparation sequences for clad and bare aluminum are given in the following paragraphs. Aluminum honeycomb core requires only vapor degreasing and baking. Some aluminum details are classified as skin quality and are closely controlled. Protective coatings are used to protect the aluminum details during the various fabrication steps.

The phosphoric acid anodize process developed by Boeing is a surface treatment that adds environmental durability to the art of bonding. Also, it enhances the manufacturing cycle by increasing the time interval between cleaning and priming from 16 to 72 hours.

After the details or assemblies are degreased, they are oven dried for the time and temperature specified for the core with or without foam. Those assemblies that are completely closed should be dried in hot air where the temperature does not exceed 140°F. Next, the surface is abraded with Scotchbrite, Type A, until an oxide-free surface is obtained.

Flow coating (pour coating) with primer is essential in areas of an assembly that require the core details to be at their original strength. Flow coating adds that protection. Flow coating is applied mainly to the crushed-edge and laminated-edge honeycomb core. Other core details for square or trailing edge or spar core may also be flow coated.

First, the noncoated areas of the honeycomb core details are covered with wax-free paper. The liquid primer is applied to the open areas with a pressure-feed gun equipped with a wing tip nozzle. The primer should completely cover each cell wall. When the liquid primer is drained sufficiently, the core detail is hung on a rack to air dry. This is done with the core cells in a horizontal position. When time has lapsed for the air dry, the rack and core are rolled into a bake oven, where the primer is baked per the specification for each adhesive system.

Spray coating is the application of an adhesive primer with a pressure-feed spray gun. First, the panel areas that are not to be bonded are covered with a masking template or sealed off with masking tape. Then a liquid adhesive, to which thinner has been added, is sprayed over the area to be bonded, producing a fine, even coat of adhesive on the surface of the metal. The spray gun should be held square with the details while spraying. Spray coating is done by certified operators. The details are then air dried and oven baked per specification.

4.8.3 Peel Plies, Release Films, or Fabrics.

Uncontaminated faying surfaces, the surfaces that are adhesively bonded together, are required to attain reproducibly strong bonded joints. Peel plies for that purpose provide maximum protection to the faying surfaces during subsequent operations prior to the application of adhesives. Peel plies are ordinarily removed just prior to the bonding or secondary coating operations. However, the use of peel plies does not remove the requirement to lightly abrade the surface before bonding.

Release films and fabrics serve many purposes. Some are used as separators between successive layers of prepreg. Some serve as backings for carrying precut plies of prepreg to the mold. Others are used to provide cleavage between the composite construction and the bleeder plies used to absorb the excess resin from the lay-up during the bag molding cure.

Even though they leave no residual contaminants, some release films and fabrics are unsuitable for peel plies because they cannot adhere to the composite surface. On the other hand, greige fiberglass fabrics are often used as peel plies even though residual oil-starch size remains on the composite surface after the fabric is removed. However, before the secondary or bonding operations, the residual size is removed by sanding or by solvent wiping. The adequateness of such surfaces for adhesive bonded structures should be verified.

Peel plies for some architectural adornments and constructions for interiors are fiberglass fabric greige goods. After the peel plies are removed, the exposed surface textures complement the patterns of the reinforcements or the decorations.

The most popular materials for peel plies are the commercially available heat-cleaned and scoured nylon, heat-cleaned lightweight fiberglass, and the suitable polyester release fabrics. User preferences for target surface textures vary. Some prefer stronger fabrics and accept coarser weaves. The secondary sanding operations for refining textures are less costly than removal of

finely woven peel plies. Other companies use the finer weaves that leave textures requiring no additional refinements. Most commercial peel plies are square weave fabrics not ordinarily conformable to dished or contoured shapes. Military Specification MIL-Y-1140 lists more conformable satin fabrics of heat-cleaned fiberglass. Styles 120 and 2120 are the preferred lighter weaves.

4.8.4 Control of Process.

Structural adhesive bonding is not one simple operation but a complex sequence of operations. The success of each step depends on everything that has been done up to that point. At every step in the bonding process, both the operator and the inspector must exercise the highest degree of control in strict accordance with the process specification for each individual job.

The entire bonding process must be carefully controlled in order to ensure the reliability of the bonded assembly. With a bit of carelessness here, a moment of inattention there, even an inadvertent fingerprint, the entire end product of everyone's efforts may have to be discarded. Therefore, careful attention to work cannot be overemphasized. Some typical defects that can be expected are illustrated in figure 25.

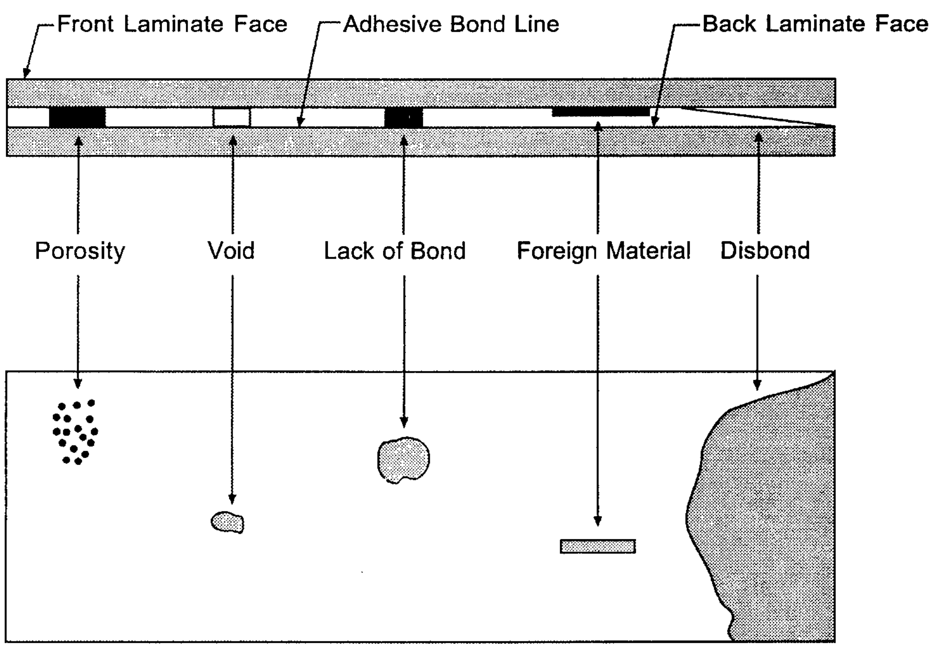


FIGURE 25. ADHESIVE BONDING DEFECTS

Engineering specifications lay down the ground rules for structural adhesive bonding; manufacturing directions give the how to rules for techniques and procedures, and the quality control inspectors are the umpires. Familiarity with the applicable process specifications for each individual bonding process will minimize rework.

4.8.5 Work Environment.

The area where surface cleaning of the details is to be accomplished is usually isolated from operations that generate dust, oil, vapors, or other contaminants. All personnel handling cleaned details shall wear clean, white, lint-free cotton gloves. Immediately after cleaning, details are moved into an area with a controlled atmosphere for adhesive primer application. Adhesive lay-up and bagging operations that generate dust or other airborne contaminants in the controlled area and activities such as sanding or grinding are forbidden. Similarly, smoking or eating is also forbidden.

4.9 QUALITY ASSURANCE BOND SPECIMENS.

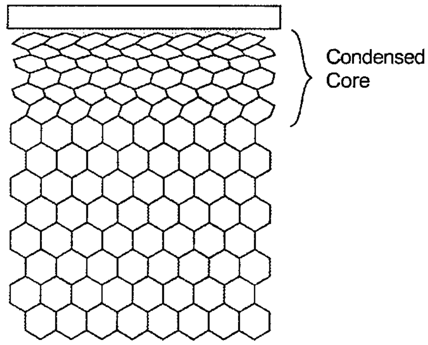
When any bonded assembly is going through a cure cycle, test specimens will be fabricated using the same materials and processes as the bond assembly and will accompany the bonded assembly during cure. The purpose of these specimens is to verify the bonding process. Usually the two types of tests conducted are shear and peel tests. Any test specimens that fail requirements can be the cause for rejection of the bond assembly.

4.10 HANDLING AND STORAGE.

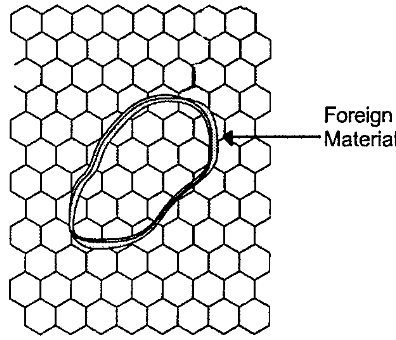
The thin metals used for adhesive bonded assemblies must be able to withstand the stress induced by aircraft takeoff, flight, and landing. The slightest damage before, during, or after bonding will make them unfit for such rugged service. A scratch on a section of clad aluminum or a bruise (buckle) in a honeycomb core can cause the complete failure and rejection of the assembly.

Careful storage, transportation, and handling of sheet metal and honeycomb core are absolutely necessary. Aluminum honeycomb core should be stored between protective faces. When stacked, honeycomb core sections must be separated with sheets of wax-free paper. Sheet metal should be stored with special care to prevent damage to edges and corners. While in transit, all metal surfaces must be protected from contact with each other or external objects. Careful handling is important at all times, from prefitting through final distribution. Some of the more typical damage for both metal and composite core is shown in figure 26.

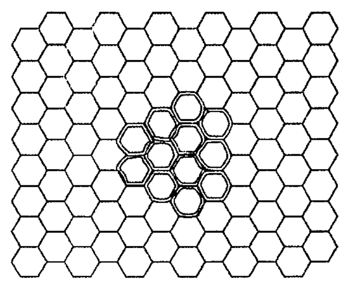
Care in preventing unnecessary contact between the material, skin, clothing, tools, or equipment cannot be overemphasized. Soiled areas should be washed as soon as possible with alcohol or a recommended cleaner, followed by soap and water. Disposable paper towels and covering for bench tops and work areas are suggested as a means of preventing accidental spreading of the liquid materials.



Condensed Core



Inclusion, i.e., Rubberband



Chrushed Core

FIGURE 26. TYPES OF CORE DAMAGE

Composite parts have similar susceptibilities to damage as metal parts. However, there are some unique things that make composite parts used in an aerospace structure more susceptible to damage. Most parts are fabricated using thermoset materials that use cure cycles involving heat and pressure. After a series of these cure cycles are used in cocuring parts, it is possible to inflict damage to the composite part by virtue of exceeding the environmental conditions that the resin can sustain. Also, repetitions of pressure during the heated cure cycle can cause some deformation to the original structure that also may be a composite part. However, the main culprit is still the temperature cycles that are higher than the environmental conditions acceptable for the use of that composite in the structure.

Another area of concern in the manufacture of composite parts is their inability to withstand some of the standard machining operations without changes in the rates of feed and types of cutters or drills that are used. Most machining operations create friction, which creates heat. This can damage the composite part. An example would be where a composite laminate has edges exposed and the laminate is made of several plies. A drilling operation or sawing operation may, in addition to supplying heat to that section, also cause the part to vibrate and delaminate. It could help destroy the resin matrix bond between the individual plies of the laminate.

Another susceptibility of the composite structure is similar to a sheet of plywood. When drilling or cutting there is some breakout at the bottom of the part. In this particular case, backup material should be used to help eliminate breakout.

There have been many studies on rates of feed and types of cutters to be used, but they are not the same as metals. Machining and cutting can be the cause of delaminations or disbonds in the completed composite part. Some of these may not be discernible to the eye and subsequent inspection by some nondestructive evaluation may be necessary to insure that the machining operation did not cause damage to the parent structure.

Composite materials, unlike metals, are usually composed of plastics that have different expansion rates than metals. If metal and a resin fibrous interface are joined to form a composite structure or a composite, materials are laid up and formed on metal tooling and allowances are necessary to compensate for the differences in the thermal expansion. The difference in expansion can cause stress in the part. This may cause future failure of the composite part. In a case where metal is actually bonded to a composite material made from fibers and resins, the adhesive used should be elastic enough in order to allow for differences in thermal expansion and contraction during the heated cure cycle. The differences in thermal expansion between the metal and composite would cause the adhesive interface to be placed under stress. Adhesives should be chosen so that they have some elasticity after cure, or they are adhesives that have the lowest possible cure temperature. Thus the differences in expansion rates of the parent materials become minimal.

Another area of concern that can cause damage to composite materials is during handling and storage. Most resins and/or prepregs are stored at low temperature and as such become brittle and can be damaged. Also, it's possible that prepreg materials or resins can be out of cold storage for too long a period. Hence, they would not be suitable for use in the composite part. Traceability of the base materials that go into making a composite part is important so that the allowed out time of the material will not be exceeded. Another area of concern is in handling composite parts, especially those of sandwich construction where the core materials can be easily damaged. Skin materials can be scratched much more readily than metals. Composite materials and parts are generally lighter than their metal cousins and as such are easier to move around and therefore can be damaged using the same force that we would use to move around and lift up the metal parts.

5. MANUFACTURING METHODOLOGY.

5.1 INTRODUCTION.

The manufacturing methods of materials chosen for their special mechanical properties are built upon the principle of optimizing the properties of those materials. Therefore, whenever compromises have been required in choosing a manufacturing method versus mechanical property, the tendency has been to choose the property.

In most aerospace applications that trend will continue, and it is the job of the fabricator to thoroughly understand the manufacturing methods in order to maximize the mechanical characteristics of the properties.

In other applications, the mechanical properties can be compromised to some extent to achieve improved economics in the manufacturing method. Good mechanical properties will always be important; if not, why would one choose composites as the material? Still, the ultimate properties may not be required and cost reductions from manufacturing improvements may be possible. Because thermoset composites dominate in actual use, most of the manufacturing methods that will be discussed are best suited to thermosets. In addition, even some of the traditional thermoset methods are being adapted for use with thermoplastics.

The two principal steps in the manufacture of laminated fiber-reinforced composite materials are lay-up, which consists of arranging fibers in laminae and laminae in layers or laminates, and curing, which is the drying or polymerization of the resinous matrix material to form a permanent bond between fibers and between laminae. Curing may occur unaided or consist of applying heat and/or pressure to aid polymerization. When pressure is used, processes include vacuum bag, autoclave, hydroclave, and tool press. Lay-up can be accomplished by hand or by automated processes. Newer techniques are being developed to bypass lay-up and replace it with automated textile technology and other more direct methods.

5.2 HAND FABRICATION.

The simplest technique, and probably the first used to make a modern composite structure, is called lay-up, lay-up molding, wet lay-up, or contact laminating. In this method, fabric or mat is saturated with liquid resin and the lay-up is made by building layer upon layer to obtain the desired thickness. The impregnation of the layers is done at the time the material is laid into the mold. This method is used most extensively with polyester and fiberglass, although some epoxy-fiberglass composite parts are also laid up wet.

A somewhat superior product can be made, with less resin and fiber handling difficulty, by using a reinforcement that has been preimpregnated with resin and then cured slightly to increase the viscosity. This material is called prepreg. Normally, the prepreg is produced at a facility dedicated to its manufacture that allows careful control of the resin and fiber contents. It is then

shipped to the composites manufacturing site. Prepregs are used in applications in which the performance of the part is critical.

In both methods, wet and prepreg lay-up, the layers are placed onto a shaped surface (the mold) by hand. Some pressure is normally applied by hand rolling, wiping with a squeegee, or using vacuum bagging to remove trapped air and provide better uniformity. Curing can be done at room temperature or at elevated temperatures.

5.2.1 Wet Lay-Up Method.

The oldest and perhaps the most common method of wet lay-up involves laying the dry reinforcement (most often a fabric or a mat) into the mold and then applying a predetermined amount of resin. The wet composite is rolled by hand to evenly distribute the resin and to remove air pockets. Another layer of reinforcement is laid on top, after which more catalyzed resin is poured, brushed, or sprayed over the reinforcement. This sequence is repeated until the desired thickness is reached. Then, the layered structure is allowed to harden (cure).

This method is conceptually simple, does not require special handling of wet fabrics, and allows the resin to be applied only in the mold, thus helping to maintain a neat working area. However, variances in resin viscosity inherent in the gradual curing of precatalyzed resins may cause problems in getting good wet-out (if too thick) or in having resin runoff (if too thin). The part shape may also cause difficulties in proper wet-out.

Even when using a wet method (which is where the technician applies the liquid resin), better uniformity is usually possible if the reinforcement is prewetted with the resin before being laid into the mold. The dry fabric and liquid resin can be weighed to obtain specific fibery/resin ratios. On a flat surface, the weighed resin can be rolled or squeegeed into the fabric more uniformly than on a tool because the areas of excess resin are more apparent.

Costs are better controlled on large structures through this method of prewetting the reinforcement because it serves to reduce the amount of excess resin required to wet out the fabric. This method also helps prevent the formation of resin-rich and resin-poor areas caused by vertical drainage. Runoff of excess resin on a male mold will flow off the lay-up so that wetting the glass with excess resin will not present a critical problem. Nevertheless, this method is rarely used because of the difficulty of handling a wet sheet of reinforcement. When a mat is used instead of fabric, the mat is generally saturated with resin on the mold to prevent unraveling and distorting during the transfer process.

To prevent the composite from sticking to the mold, a mold release or parting agent is first applied to the mold. This mold release can be silicone, polyvinyl alcohol (PVA), fluorocarbon, or in some cases, a plastic film. This is discussed more fully in the section on tooling.

For many commercial applications a layer of catalyzed resin is applied to the release-coated mold and is allowed to cure to the gel (tacky) state before the dry or saturated reinforcement is applied. This resin layer, or gel coat, forms a protective surface layer through which fibrous reinforcements do not penetrate. Specially formulated gel coat resins are used to improve flexibility, blister and stain resistance, weatherability, and toughness.

Another approach to improving surface characteristics involves wetting out a fine weave fabric, such as 120 style fiberglass directly on the released mold, followed by thicker woven reinforcements. This method guards against the creation of a resin-rich surface that can crack and craze, especially if the structure is subjected to flexural stresses. In either approach, finer weave fabrics are normally used near the surface of the part to prevent transfer of the weave pattern to the surface and because air and voids can be removed more easily from these finer materials.

Although not specifically required in the process, many manufacturers using the wet lay-up method obtain improved parts by using a vacuum bagging method. Described in detail in the section on vacuum bagging, this method involves placing a vacuum bag over the lay-up and then securing it to the mold around the edges. A vacuum is drawn inside the bag, removing the bubbles in the part and compressing the lay-up to achieve good wet-out and definition against the mold.

Parts are removed by manually pulling them from the mold. To assist in the removal, flat wooden, plastic, or metal wedges can be inserted between the part and the mold. Some manufacturers also blow low-pressure air into this gap to lift the part from the mold or put air ports into the sides of the mold to allow air to be introduced. Mechanical assistance is sometimes needed if the part is large.

Because curing of wet lay-ups is usually done at room temperature, a promoter is often added to the resin to speed up the reaction. Caution must be observed to ensure that the promoter and the initiator (catalyst) are never directly mixed together. Each of them should always be mixed into the resin in separate steps. External heating with infrared lamps or hot-air blowers are sometimes used to accelerate the curing process.

The advantages of wet lay-up include the following:

- Tooling can consist of any material that will hold its shape under minimal pressure.
- Tooling can be changed easily during the experimental phase or to accommodate engineering redesign.
- Although a vacuum pump is often used with epoxy parts, investment in pressure devices such as a press, autoclave, or vacuum pump is not required.
- Curing ovens are not needed.
- Semiskilled workers can be easily trained.

The following are among the limitations of wet lay-up:

- Only certain types of resin can be used because other types require some form of pressure to avoid porous, poorly laminated structures.
- Product uniformity, both within a single part and from part to part, is difficult to maintain. Because of inability to compact laminate with any pressure, the resin content is often quite high.
- Voids are common.
- Mechanical properties are low in comparison with other composite manufacturing methods.
- Tight-weave fabrics are difficult to saturate with high-viscosity resins, resulting in low strength.
- Draining from vertical walls can be a problem. Although most resins have the appropriate viscosity to prevent puddles near the base, resin-poor areas in the wall can develop.
- There is shrinkage from resin-rich areas.
- There is one finished surface.

5.2.2 Prepreg Method.

The prepreg method can, in some regards, be viewed as an extension of the wet lay-up methods previously described, prewetting outside the mold and then laying up the composite. In prepregging, the fibers are usually arranged in a unidirectional tape or a woven fabric, impregnated with initiated resin, partially cured, and then rolled up for shipment. The prepreg lay-up method is much more precise than the wet lay-up method. However, the prepreg method usually requires vacuum bagging and autoclaving (discussed later). In the prepreg method, the prepreg, which is supplied in rolls of convenient widths, typically 12 to 60 inches (300 to 1520 mm) wide but as narrow as 3 inches (75 mm) and up to 72 inches (1830 mm) wide, is normally cut to fit into the mold and laid up layer by layer until the desired thickness is achieved.

Prepregs used for manual lay-ups are leathery and require a slight tackiness (tack) so that the layers will not slide over one another during lay-up and maintain their location in the mold. The prepreg should also be conformable to the mold so that complex shapes can be produced. This ability to conform is called drape. Drape and tack are often associated with one another and are dependent on the resin. Reactive-thermoplastic resins are often stiff at room temperature and

have almost no tack or drape. Therefore, they may be melted slightly with a hot-air blower or a soldering iron to make tacking the layers together easier.

Although the laminate resin content is controlled during the resin fabrication step, the resin content of the prepreg influences the tack and drape as well as the final strength of the laminate. In many prepreg systems, the resin content of the prepreg is higher than is desired in the finished part. This lends itself to tack and drape but requires that the excess resin be removed at some point in the manufacturing process. The removal of this excess resin also facilitates the removal of entrapped air and volatiles which will flow out along with the excess resin. It is essential that this occur because voids within a laminate have a severe effect on the interlaminar shear strength. As a guide, the interlaminar shear strength reduces approximately 7% for each 1% of voids present up to a maximum of about 4% voids. A reasonable goal for void content in the finished laminate is 0.5% or less. The method for removing this excess resin is outlined in the section on vacuum bag assemblies.

Fabric prepregs are generally used on complex contours because of their ability to drape and conform to the mold. The weave of the fabric can be a significant factor in the ability to drape. Unidirectional tape naturally tends to follow a geodesic path on a contoured tool and is often difficult to use because it will not drape over complex contours and will leave gaps and overlaps in severe cases.

Traditionally the resin content of the prepreg is given as a weight percentage; whereas, the resin content of the finished part is given as a volume percentage. The explanation for this is simply that when the prepreg is made, the resin weight percentage is easy to measure and control. However, the resin (or fiber) volume percentage is preferred for finished laminates because it is related directly to the mechanical properties. Historically, the trend has been towards lower resin content so that the specific strength of the composite is increased. Because consistent removal of large excesses of resin has become a costly problem, prepregs are now made with near-net resin contents. These prepreg materials are generally produced through a hot-melt impregnation method that minimizes the volatiles remaining in the prepreg. Voids from entrapped air are minimized by debulking the material (vacuum or autoclave) after laminating three to ten plies of material. Most aerospace laminates today are approximately 60% fiber volume fraction.

Because the resin has already been initiated when the prepreg is made, prepregs have a limited shelf life. Eventually, the prepreg turns into a dry and boardy material that is difficult to use. The shelf life is usually several days to weeks at room temperature but can be extended by keeping the prepreg cold. The out time, or time out of the freezer, is recorded so that an estimate of the remaining useful life of the prepreg can be made. Standard tests are available to determine more precisely the percentage of curing that has occurred in the prepreg, thereby calculating the approximate remaining shelf life. Many prepreg resins require heat to react and cure. If parts are laid up in a mold prior to losing tack, their life at room temperature is often very long. Upon heating, the resin will flow and cure to its full cure state, even though it appeared to be cured prior to heating.

The unidirectional prepreg tape and fabric are laid up as continuous strips. The location of adjacent strips is controlled by drawing tolerances that specify the allowable dimensions of the gap and overlap (see figure 27).

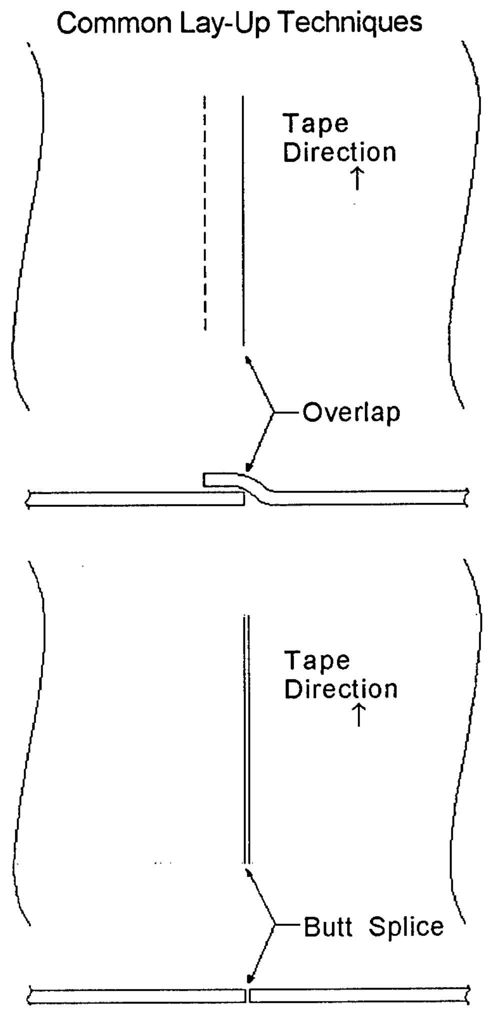


FIGURE 27. PREPREG SPLICING

5.2.2.1 Advantages of the Prepreg Method.

- The resin/initiator (or hardener) ratio is more accurately controlled during the premixing operations.

- Resin distribution per unit area is strictly controlled during prepreg manufacture. This aids greatly in providing good resin distribution in the final part.

- Health and safety problems associated with liquid resins or solvents are largely eliminated because these are handled by the prepreg manufacturer who is often better prepared to deal with them.

- The problems of poor efficiency and output can be reduced by using automated machinery for some parts.

- These methods offer better part definition, higher fiber content, and better consolidation than wet lay-up.

5.2.2.2 Disadvantages of the Prepreg Method.

- This method is slow and labor intensive compared to automated methods.
- There is a potentially high reject rate because of faulty bagging procedures.
- It is difficult to bag complex shapes.
- Curing equipment (autoclave) is expensive.
- Inside surfaces are not as satisfactory as in matched-die molding.
- The cure cycles are long compared to matched-die molding.

5.2.2.3 Cutting and Kitting of Prepregs.

The cutting of the prepreg material, prior to lay-up, is the first step in the fabrication of composite aircraft structural parts. The resources used to cut the prepreg material fall into five basic categories: manual, reciprocating knife, gas laser, water jet, and die blanking (see table 7). A brief description of these cutting methods is presented below.

The manual cutting of the prepreg is the simplest method and the least expensive in terms of capital investment. This method requires templates, made of steel or aluminum, that resemble the various layers in the part. The operator lays the template on the prepreg material and runs a razor knife or pizza cutter type tool around the template (see figure 28). The primary drawback to this type of cutting is the chance of human error in aligning the template for proper fiber orientation of the ply. However, manual cutting of prepregs is widely used throughout the industry.

The reciprocating knife concept is borrowed from the garment industry. The popular brand name that is usually associated with the reciprocating knife is Gerber. The Gerber knife is operated by a computer program in the same way a milling machine is numerically controlled. The cutting is accomplished by a knife that reciprocates up and down, with its lateral movement controlled by the cutter head via signals received from the computer program. The Gerber knife requires a special table to cut the prepreg on. The table surface is covered with nylon bristles that allow the knife to cut the prepreg and descend past the prepreg into the bristles. Before initiating the cutting of the prepreg, the material is covered with a mylar film. The mylar allows a vacuum to be drawn through the bristles to hold the prepreg to the table during the cutting operation. The reciprocating knife method of cutting the prepreg requires a sizable investment in personnel training and equipment, but it is a fast process and ensures high accuracy of the cut dimensions.

TABLE 7. MATERIAL CUTTING TECHNIQUES

TECHNIQUE	ADVANTAGES	DISADVANTAGES	APPLICATION
Manual	Flexible, limited set-up time, economical for narrow tape	Slow, tedious, labor-intensive, requires Mylar and templates, costly inspection, difficult to cut multiple plies	3, 12, 48 in. wide (76, 305, 1220 mm) tape and broad goods fiber-glass B-Ep, Gr-Ep, and Kv-Ep
Gerber knife (reciprocating knife)	Fast, 720-1200 in/min (305 to 508 mm/s) computer controlled, reliable for textiles, clean cuts, reliable up to 20 plies, accuracy ± 0.030 in (0.76 mm)	Accuracy less that that of laser and water jet, knife gumming with some resins	Cutting uncured prepreg composite materials
Laser	Cut B-Ep at 540 in/min (330 mm/s), computer controlled, takes wide material	Basic cost and energy cost high, limited number of plies, eye protection required	Cutting cured and uncured composite materials
Water jet	Generates no dust, multiple-ply cutting to 40 plies, no heat-affected zone at edges, computer controlled, takes wide materials	Slight moisture absorption in uncured prepreg material, limited number of plies	Cutting cured and uncured composite materials
Steel-rule die	Generates no dust, multiple-ply cutting (to 15 plies), no heat-affected zone at edges, takes wide materials, clean cuts	Design change require die change	Cutting uncured prepreg composite material 4, 12, 48 in (76, 505, 1220 mm) widths

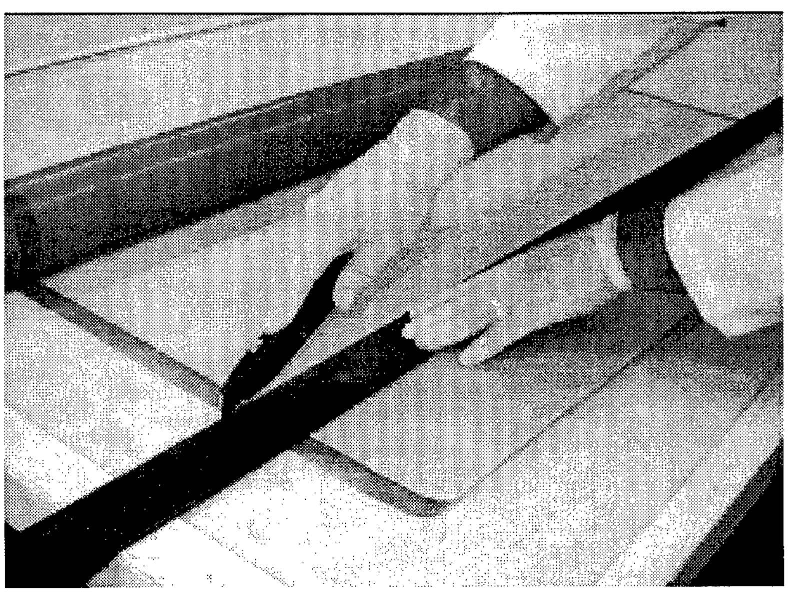


FIGURE 28. CUTTING PREPREG WITH KNIFE

The use of carbon dioxide gas laser for cutting prepregs is not widespread. The light beam is focused down to a small spot and causes some localized prepreg heating that does not seem to have any detrimental effects. The surface of the cutting table is usually made of aluminum and is replaced after it becomes heavily scored. An advantage in cutting with laser beams is that the work environment is noise free and comfortable.

There are limited applications for cutting prepregs using a water jet. This method requires water to be forced, at high pressure, through a small orifice to form a very precise cutting stream. The action of the nozzle head is controlled by a computer program similar to the laser or reciprocating knife cutting technique. Usually the use of water jets requires a means of collecting the water and a disposable table surface. The absorption of water by the prepreg has been of concern but has not proven to be a significant problem.

5.3 AUTOMATED LAY-UP PROCESSES.

The four principal automated lay-up processes for laminated fiber-reinforced composite materials are filament winding, tape laying, fiber placement, and molding. The choice of both the lay-up and the curing process depends on process effectiveness, part size, schedule, and cost.

Filament winding consists of passing a fiber through a liquid resin and then winding it on a mandrel. Fibers are wrapped at different orientations on the mandrel to yield many layers and hence strength and stiffness in many directions. Subsequently, the entire assembly is cured on the mandrel, after which the mandrel is removed.

Tape laying starts with a tape consisting of fibers in an preimpregnated form held together by a removable backing material. The tape is unwound to form the desired shape in the desired orientations of tape layers.

Fiber placement is the marriage of numerous technologies into a single piece of equipment. Filament winding is an economical method of fabricating simple cylindrical-type geometries. Tape laying strives to address contoured but nonrotating geometries and has excelled at large relatively flat applications. Fiber placement allows the automated lay-up of materials like a tape layer but enabling more precise placement and more complex contours.

5.3.1 Filament Winding.

Filament winding is a comparatively simple operation in which continuous reinforcements in the form of rovings or monofilaments are wound over a rotating mandrel. Specially designed machines, traversing at speeds synchronized with the mandrel rotation, control the winding angles and the placement of the reinforcements. These may be wrapped in adjacent bands or in repeating patterns which ultimately cover the mandrel surface. Successive layers are added at the same or different winding angles until the finished thickness is reached. The wrap angle may vary from low-angle longitudinals to high-angle hoops approaching 90 degrees relative to the mandrel

axis and any helical angle may be wound between these limits. A thermoset resin serves as a binder for the reinforcements. In wet winding, the resin is applied during the winding stage. The alternate dry winding method utilizes pre-impregnated B-staged rovings. Normal curing is conducted at an elevated temperature without pressurization, and mandrel removal completes the process (see figure 29). Finishing operations, such as machining or grinding, may be performed if required.

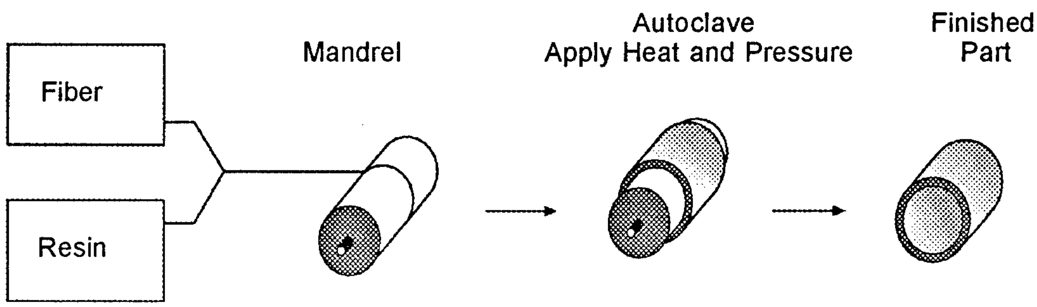


FIGURE 29. FILAMENT WINDING

The basic process is subject to numerous variations offering a broad spectrum of structural types, design features, material combinations, and equipment. Structures are necessarily wound as surfaces of revolution, although within limitations other shapes can be formed by internal pressurization of an uncured winding in a closed mold. Structures may be plain cylinders, pipe, or tubing, varying from a few inches to several feet in diameter. Spherical, conical, and geodesic shapes are within winding capability.

End closures can be incorporated into the winding to produce pressure vessels and storage tanks. The structures can be designed for specific loading conditions such as internal pressure, external pressure, and torsional or compressive members. Combination winding is another possibility, where hoop overwraps are added as reinforcement to thermoplastic pipe or metal pressure vessels. Parts can be designed and fabricated with a high degree of precision. On the other hand, the winding may be geared to less critical fast rate production.

Virtually any continuous reinforcement is suitable for winding purposes. In practice, filament winding manufacturing primarily utilizes fiberglass as the choice of material. Graphite fibers and the aramid fiber, Kevlar 49, have been adapted to the more exacting space and aircraft applications, where high strength and modulus are major considerations.

The principal matrix materials are epoxy, polyester, and vinyl ester resins. Polyimides, phenolics, and silicones, which yield condensation products on curing, are processed with greater difficulty. Currently, interest is being directed to the utilization of certain thermoplastics for specific applications.

Winding machines vary from lathe types or chain driven machines to more complicated computerized equipment with three or four axes of motion. Machines have also been built for

the production of continuous pipe. In another variation, portable equipment has been designed for winding large storage tanks on location. These machines normally lay down only hoop windings, while the longitudinal reinforcement is provided by either chopped strands or broad goods.

5.3.1.1 Description of Process.

The filament winding process can be described as a precise lay down of continuous reinforcement in predetermined patterns. This process entails continuous resin-impregnated rovings (gathered strands of fiber) wound over a rotating male mandrel. The mandrel can be cylindrical, round, or any shape that does not have a re-entrant curvature.

A filament winding machine is similar in concept to a lathe. A lathe suspends a cylindrical piece of metal between two points, and rotates it at a given speed. A cutter precisely removes material of various quantities and configurations while the metal is rotating, leaving a specified symmetrical shape cut.

A filament winding machine precisely places material on to a metal mandrel in a similar manner as the lathe removing material from a metal mandrel. The filament winder has a movable head that orients the reinforcement fibers onto a mandrel. A filament winding machine pulls continuous fiber through a resin bath and places it on a mandrel for curing. The fiber wound mandrel can be removed from the winder and processed in a room ambient cure or placed in an oven or autoclave for processing.

The most important advantage of filament winding is the cost savings during manufacturing. Cost reductions occur because of the high-speed fiber lay down and relative low cost of materials that are involved. Other important advantages are (1) highly repetitive nature of fiber placement from layer to layer and from part to part, (2) the capacity to use continuous fibers over a whole component area without joints, and (3) to orient fibers in the load direction. Large structures can be built providing lower cost because large numbers of components are eliminated. Fibers can be specifically placed in the load direction.

This process is ideal for tubular structures such as masts and poles in the marine industry where light weight, high performance, and corrosion resistance are required.

5.3.1.2 Equipment, Tooling, and Supplies.

One benefit from the filament winding process for composites manufacturing is the simplicity of tooling. A mandrel which provides the part with its internal geometry is usually the only major tool. Mandrel design depends on the geometry required for the finished part. A simple steel cylinder, ground to the proper diameter, is used for cylindrical items such as pipes and simple drive shafts (see figure 30). Most mandrels are steel tubes ground to size with an axis welded in place on each end which is held in the winder head and tail stock. After cure, the part is pulled

off the mandrel. Other cylindrical designs may require shapes on the inside or outside of the finished part. This can be accomplished with removable tooling components.

The typical equipment would be a filament winder and mandril, which can range in cost from $15,000 to $350,000. Other small tools are required for this process, such as scissors, brushes, squeegees, and gloves.

The most widely used fiber for filament winding is fiberglass due to its performance-to-value properties. The more expensive materials such as carbon fiber and Kevlar are also used where high-performance attributes are a priority in design. These materials are typically purchased in roving form about 1/8 to 1/4 inch diameter and wound on large spools or rolls.

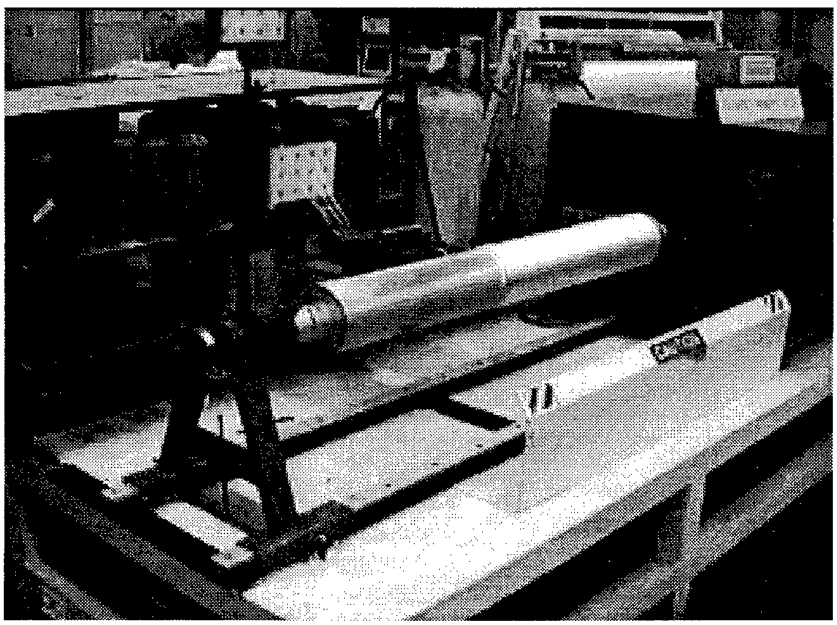


FIGURE 30. FILAMENT WINDER

Ninety percent of filament winding uses a wet resin system as opposed to a prepreg resin system. The wet system means the resin is catalyzed and placed in a bath. The dry fiber is pulled through the wet resin and then wound on to the mandril as the mandril is spinning. This resin system must be used in conjunction with the fiber of choice in order to bind each strand of fiber to one another to make up a composite component. Several resin systems can be utilized for this process. The most common would be polyester resin systems, vinyl ester resin systems, and epoxy resin systems.

5.3.1.3 Shop and Work Space Requirements.

A typical filament winder needs an area of approximately 4 by 10 feet. There are smaller units available that will make small composite parts requiring only half that floor space. There are also

much larger units that require 100 feet of shop space in order to operate. An average filament winder may require additional electricity for start up or operation.

The shop environment in which this process will take place requires reasonably clean and dry conditions. The product quality is partly dependent upon a shop environment that is clean and free of airborne contaminants. Typically the wet resin system requires temperature and humidity controls in order to control the advancement of the cure.

Due to the availability and cost of equipment and material, it is safe to say that filament winding facilities are more prevalent than tape laying facilities. Filament winding technology lends itself well to the marine, aerospace, sporting goods, automotive racing, and other related industries. Structures requiring a cylindrical or tubular shape can be fabricated with this process which allows many manufacturing facilities to utilize this effective tool.

5.3.2 Tape Layer.

After advanced composites were introduced in the early 1960's, it was soon learned that carbon fibers were brittle and abrasive. When woven into fabric, fibers were prone to breakage and lost a significant amount of their strength. In turn, unidirectional tapes became the preferred material form for processing carbon fibers. Originally the advanced composite tapes were laid up by hand on to the mold or tool. This process was labor intensive, and it was found that irregular placement of the tape caused the quality of cured laminates to be inconsistent. Therefore, aerospace companies began to develop tape-laying machines.

A typical tape-lay process is conducted via an automated numerically controlled machine. It could be described as being similar in concept to a gantry type, three or five axis milling machine in that it has the capability to orient itself on an X, Y, Z, and/or A and C axis to the tooling. The difference being, a milling machine removes material from an object, and a tape-laying machine places material on an object or tool. A major advantage of a tape-laying machine is that it can provide a labor savings of up to 85% over the hand lay-up process. Other advantages include minimized waste, improved structural properties, repeatability and consistency, greater control, and an overall quality improvement. This advanced process will yield higher production rates as opposed to conventional hand lay-up applications.

5.3.2.1 Equipment and Supplies.

A tape laying machine can be as large as 40 feet long and 10 feet wide or as small as 6 feet long and 3 feet wide. Machine size, as well as cost, is governed by the size and complexity of the part. The cost of a machine can range from $100,000 to $2,000,000.

Typical materials are carbon fiber tape, fiberglass tape, Kevlar tape, and boron tape. The tape comes in various widths and specifications. Other shop tools needed are the standard tools associated with hand lay-up such as scissors, razor blades, and gloves.

5.3.2.2 Shop Space Requirements.

The physical size of the unit determines the space needed to operate it efficiently. The work space should be temperature and humidity controlled as well as dust free. Generally, this equipment requires a generous amount of electrical power to operate so additional power and local city permits might have to be obtained to meet the electrical requirements.

5.3.2.3 Manufacturing Environment.

The majority of the manufacturing facilities utilizing this process are aerospace and aircraft companies. Typically any aerospace contractor requiring precision fiber placement technology for volume production will utilize some form of tape laying to fabricate the composite structures or parts.

5.3.3 Fiber Placement.

Fiber placement is a single process that takes advantage of both filament winding and tape laying. Fiber placement utilizes the differential layout capability and fiber delivery of winding with the compaction and restart features of tape. A schematic of a fiber placement process is shown in figure 31.

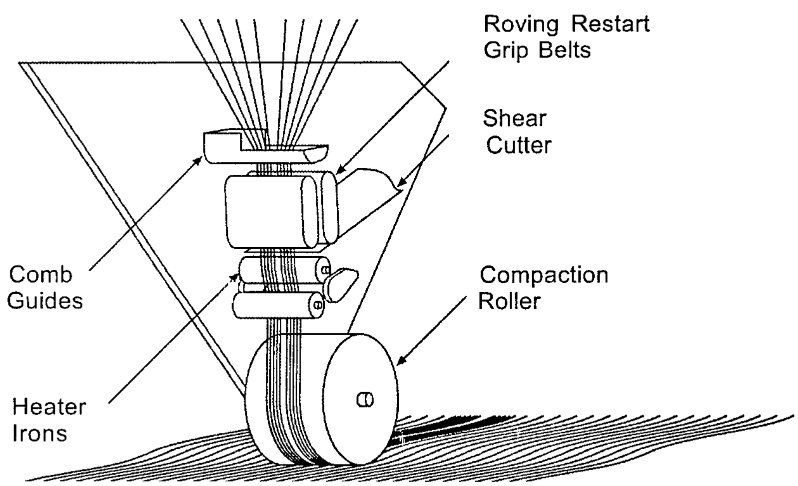


FIGURE 31. AUTOMATED FIBER PLACEMENT

5.3.3.1 Description.

Fiber placement is the marriage of numerous technologies into a single piece of equipment. Filament winding is an economical method of fabricating simple cylindrical-type geometries. While tape laying strives to address simple contoured but nonrotating geometries, it has excelled at large relatively flat applications. Both have made a positive impact on the reduction of time needed for hand lay-up.

5.3.3.2 Fiber Placement Process Development.

The Boeing company developed and patented a fiber placement process in the early 1980s and developed a functioning twelve-ribbon machine and licensed the technology to Cincinnati Milacron (CMI). Currently being tested are several programs with outside sources of fiber placement technology supporting the High Speed Civil Transport (HSCT) and the New Large Subsonic Airplane Program development, with plans to conduct intensive, in-house development in the future. Following are some of the fiber placement advantages.

- Material can be put exactly where needed
- Low scrap rate
- Rapid laydown rate
- Geodesic or steered path
- Pickup/drop-off of selected ribbons
- Reduced part weight
- Reduced ply count on part
- Improved contours

5.4 PULTRUSION.

Pultrusion is an automated process for manufacturing composite materials into continuous parts having a constant cross section. It is probably one of the most versatile composite processes, but it is still one of the least understood.

The term pultrusion refers to the final product and to the process. Most simply, it refers to a nonhomogeneous compilation of materials pulled through a die. In virtually every case, a continuous reinforcing fiber is integral to the process and the finished product. The matrix used is typically a thermosetting resin, which chemically reacts when heat is introduced to create an exothermic reaction. Unlike thermoplastics, the resulting profile is shaped to the point at which it cannot be reshaped or otherwise altered within its operating temperature range. In contrast, the extrusion of aluminum and thermoplastic materials involves homogeneous materials that are heated and pushed through a die and then allowed to cool into the final solid shape. Because the material is initially heated and then cooled, it can be heated again and reformed into another shape.

The pultrusion process has developed relatively slowly compared to other composite processes. There is a significant amount of art in combining the continuous reinforcements and resins in a continuous operation, and developing the science from the art has taken time. During the 1980s, there has been a dramatic increase in market acceptance, technology development, and pultrusion industry sophistication. Today, the number of technically competent personnel in pultrusion is sufficient to provide the base from which dramatic growth can occur. This, coupled with continual increases in cost-competitive advantages, will enable pultruded composites to become a traditional material alongside steel, wood, and aluminum before the end of the 20th century.

5.4.1 Process Description.

Of the six key elements in the pultrusion process, the three that precede machine operation are a reinforcement handling system (refereed to as creels), a resin impregnation station, and the material forming area. The machine consists of component equipment that heats, consolidates, continuously pulls, and cuts the profiles to a desired length (see figure 32). Although machines can produce profiles that range from 25 mm (1 inch) to 3 to 5 m (10 to 15 feet) per minute, typical line speeds are in the range of 0.6 to 1.2 m/min (2 to 4 ft/min) per cavity.

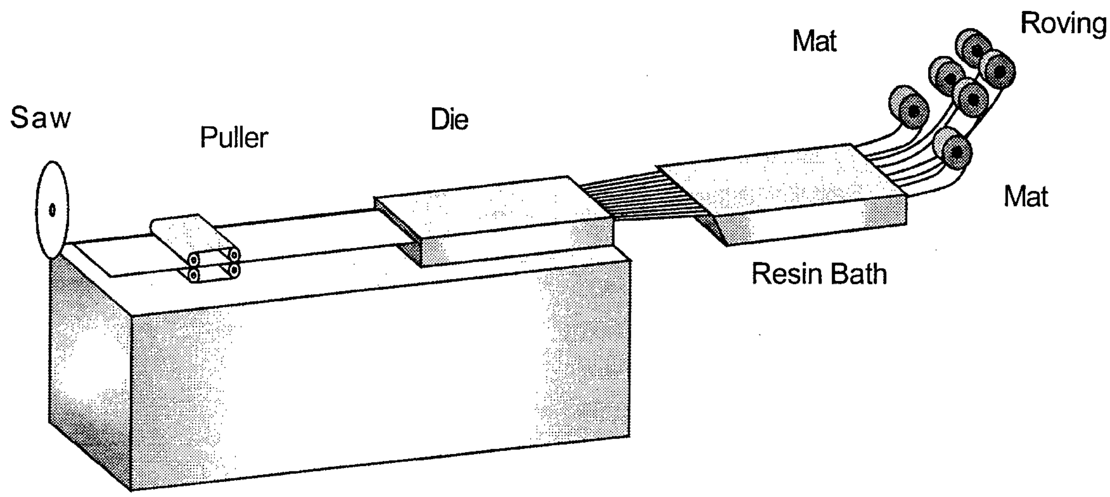


FIGURE 32. PULTRUSION

The process begins when reinforcing fibers are pulled from a series of creels. The fibers proceed through a bath where they are impregnated with formulated resin. The resin-impregnated fibers are preformed to the shape of the profile to be produced. This composite material is placed in a heated steel die that has been precision machined to the final shape of the part to be manufactured. Heat initiates an exothermic reaction in the thermosetting resin matrix. The profile is continuously pulled and exits the mold as a hot, constant cross-sectional profile. The profile cools in ambient or forced air or assisted by water as it is continuously pulled by a mechanism that simultaneously clamps and pulls. The product emerges from the puller mechanism and is cut to the desired length by an automatic, flying cutoff saw.

There are two categories of pultrusion products. The first category consists of solid rod and bar stock produced from axial fiberglass reinforcements and polyester resins; these are used to make fishing rods and electrical insulator rods, which require high axial tensile strength. The second category is structural profiles, which use a combination of axial fibers and multidirectional fiber mats to create a set of properties that meet the requirements of the application in the transverse and longitudinal directions.

More than 90% of all pultruded products are fiberglass-reinforced polyester. When better corrosion resistance is required, vinyl ester resins are used. When a combination of superior

mechanical and electrical properties is required, epoxy resin is used. Higher temperature resistance and superior mechanical properties generally dictate the use of epoxy resins reinforced with aramid or carbon fibers.

5.4.2 Process Advantages.

Pultruded composites exhibit all of the features produced by other composite processes such as high strength-to-weight ratio, corrosion resistance, electrical insulation, and dimensional stability. Additional advantages are inherent in this process. One is that any transportable length can be produced because of its axial nature, including small-diameter fiber optic cable core that is 2.2 km (1.4 miles) long, which can be wound on a spool after pultrusion. Another advantage is that complex, thin-wall shapes, such as those extruded in aluminum or polyvinyl chloride (PVC), are now possible because of recent process technology advances. Hollow sections can be produced by using cantilevered steel mandrels. A third advantage is that wire, wood, or foam inserts can be encapsulated on a continuous basis in pultruded products. In addition to symmetrical walls, which are always easier to pultrude, variable wall thickness in a constant cross section can be pultruded. A fourth advantage of the process, which is less obvious, is its ability to use a wide variety of reinforcement types, forms, and styles with many thermosetting resins and fillers. Virtually no other composite process offers as much versatility as pultrusion. Reinforcements can be placed precisely where they are needed for mechanical strength and can be consistently repeated. Finally, pultruded shapes can be made as large as required because equipment can be built in any size. A corollary advantage of larger equipment is its ability to produce multiple cavities of the same or different profiles, which enables pultrusion to compete with traditional materials because of a relatively low labor cost. The cost of dies for pultruded shapes is also low compared to other composite processes.

5.4.3 Technical Process.

The basic elements of all pultrusion machines are very similar, but there are differences in the selection of heating components, drive trains, clamping devices, and cutoff saws. A pultruder strives for a common denominator in establishing the processing system and its corresponding process control. Several commercial suppliers are available to provide a full range of hardware as well as process control features. These features help to bridge the gap between the art and experience of the established pultruders and the new companies entering the field.

5.4.3.1 Material In-Feed.

Reinforcements are provided in packages designed for the best continuous runout of its material form. Continuous glass rovings are provided in center-pull packages that weigh 15 to 25 kg (30 to 50 lb) and are designed for a bookshelf-style creel. Creels of 100 or more packages are common and may be stationary or mobile. The glass roving is usually drawn from the package through a series of ceramic textile thread guides or drilled carding plates of steel or plastic. This allows them to be pulled to the front of the creel while maintaining alignment and minimizing

fiber breakage. Some creel designs allow multiple guide eyes (bushings) or guide bars to tailor the tension to each roving. The ease of servicing or replacing roving packages must be considered in selecting a creel design and package capacity. Some fiberglass rovings are available as center-pull twistless; that is, the natural twist as a consequence of winding has been offset by a built-in reverse twist. Continuous fibers of glass, carbon, and organic polymers can also be supplied on packages with cardboard cores designed for outside pay out to avoid twist. This style of package dictates the use of a multiple spindle creel design in which the packages are oriented horizontally. Multiple bushings are again used to guide and protect fibers as they are delivered to the front of the creel. An additional consideration of package rotation and the resulting tension necessitates the use of a spindle bearing to provide uniform tension regardless of package size. Because packages in this configuration are usually smaller, a greater number of packages may be found on such a creel design.

The continuous fiber creels are usually the first station on a process line. Directly after the roving creels is a creel designed to accommodate rolls of mat, fabric, or veil. The roll materials are usually supplied in diameters between 305 and 610 mm (12 and 24 in.) with cores of 75 or 100 mm (3 or 4 in.) in inside diameter. The creel must be able to accommodate both the size of the roll and the inside diameter of the core, along with appropriate spindle spacing and core bushings. The ability to lock the position of the roll in the desired location will ensure proper delivery of the material to the desired location. In some cases, it is also necessary to provide for the pay out of web material in a vertical, rather than a horizontal, format. This requires independent stands in a lazy susan type of configuration.

As materials travel forward toward the impregnation area, it is necessary to control the alignment to prevent twisting, knotting, and damage to the reinforcements. This can be accomplished by using creel cards that have predefined specific locations for each material. In some cases, these cards can be used for only one profile. In other cases, a general format for roving and web locations can be easily adapted for a variety of common profiles.

5.4.3.2 Resin Impregnation/Material Forming.

The impregnation of reinforcements with liquid resin is basic to nearly every process. The point at which resin is supplied and the manner in which it is delivered can have many different forms. A dip bath is most commonly used. In this process, fibers are passed over and under wet-out bars, which causes the fiber bundles to spread and accept resin. This is suitable for products that are of all-roving construction or for products that are easily formed from the resulting flat ply that exits the wet-out bath. In cases in which it is impractical to dip materials into a bath, such as when vertical mats are required or hollow profiles are made, materials can pass directly into a tailored resin bath through bath walls and plates that have been machined and positioned to accommodate the necessary preform shape and alignment. This alternative method provides the necessary impregnation without the need to move the reinforcements outside of their intended forming path.

Forming is usually accomplished after impregnation, although some initial steps can be carried out during the impregnation process. Forming guides are usually attached to the pultrusion die to ensure positive alignment of the formed materials with the cavity. In the case of tubular pultruded products, a mandrel support is necessary to extend the mandrel in a cantilevered fashion through the pultrusion die while resisting the forward drag on the mandrel. Materials must form sequentially around the mandrel in an alternating fashion to prevent weak areas due to ply overlap joints. Sizing of the forming guide slots, holes, and clearances must be done to prevent excess tension on the relatively weak and wet materials but must allow sufficient resin removal to prevent too high of a hydrostatic force at the die entrance.

An alternative impregnating and forming method consists of injecting the resin directly into the forming guide or die after the dry materials have been formed. Although this technique minimizes the problems associated with the wet-out bath systems, some limitations exist in the areas of wet-out, air entrapment, and maximum filler content. A combination of techniques may be the answer for a specific profile, depending on its complexity.

The materials commonly used for forming guides include Teflon, ultrahigh molecular weight polyethylene, chromium-plated steel, and various sheet steel alloys. The pultrusion processor who employs a craftsman capable of converting sheet metal and plastic stock into forming guides with precise control would be most successful in processing complex shapes.

5.4.3.3 Die Heating.

A number of different methods can be used to position and anchor the pultrusion die and to apply the heat necessary to initiate the reaction. The use of a stationary die frame with a yoke arrangement that allows the die to be fastened to the frame is the simplest arrangement. In all die-holding designs, the thrust that develops as material is pulled through the die must be transferred to the frame without allowing movement of the die or deflection of the frame. With this yoke arrangement, heating jackets that use hot oil or electrical resistance strip heaters are positioned around the die at desired locations. Thermocouples are placed in the die to control the level of heat applied. Multiple, but individually controlled, zones can be configured in this manner. This approach is well suited to single-cavity setups, but it becomes more complex when the number of dies used simultaneously increases because each die requires a heat source and thermocouple feedback provision. Standard heating jackets can be used, and heating plates can be designed to accommodate multiple dies to help alleviate this limitation.

Another popular die station uses heated platens that have fixed zones of heating control with thermocouple feedback from within the platen. The advantage of this method is that all dies can be heated uniformly with reduced temperature cycling because changes in temperature are detected early at the source of heat rather than at the load. In the same respect, however, a temperature offset will be common between the platen set point and the actual die temperature. With knowledge of the differential, an appropriate set point can be established. When provided with the means to separate the platens automatically, the advantage of quick setup and

replacement of dies can lead to increased productivity through reduced downtime. One machinery supplier also uses the bottom platen height adjustment feature to exactly align the die centerline with the pulling mechanism to eliminate any product distortion associated with misalignment.

A source of cooling water or air is essential in the front of the die at start up and during temporary shutdown periods to prevent premature gelation of the resin at the tapered die entrance. This can be accomplished by using either a jacket or a self-contained zone within the heating platen. Alternatively, the first section of the die can be unheated, and cooling can be accomplished through convection. The most critical pultrusion process control parameter is the die heating profile because it determines the rate of reaction, the position of reaction within the die, and the magnitude of the peak exotherm. Improperly cured materials will exhibit poor physical and mechanical properties, yet may appear identical to adequately cured products. Excess heat input may result in products with thermal cracks or crazes, which destroy the corrosion resistance and the electrical and mechanical properties of the composite. Heat-sinking zones at the end of the die or auxiliary cooling may be necessary to remove heat prior to the exit of the product from the die.

To increase process rates and to reduce temperature differentials that contribute to thermal cracking in large mass products, it is desirable to deliver heat to the material before it enters the die. This is accomplished by radio frequency preheating, induction heating, or conventional conductive heating. Such heating devices are available as either integral units or stand-alone devices, which can be positioned before the die entrance.

One supplier has developed a process optimization instrument that allows tracking in a convenient graphic format of external die temperature profiles and internal product temperatures as a function of die position during the curing process. The data collected at a specific process speed become essentially a photograph of steady-state process conditions to be used for quality control, process engineering, and quality assurance documentation. Further process control developments of this nature will provide improved process capability and production efficiency.

5.4.3.4 Clamping/Pulling Provisions.

A physical separation of 3 m (10 ft) or more between the die exit and the pulling device is provided in order to allow the hot, pultruded product to cool in the atmosphere or in a forced water or air cooling stream. This allows the product to develop adequate strength to resist the clamping forces required to grip the product and pull it through the die. The pulling mechanisms are varied in design among the hundreds of machines built by entrepreneurs or supplied by commercial machinery firms. Three general categories of pulling mechanisms that are used to distinguish pultrusion machines are the intermittent-pull reciprocating clamp, continuous-pull reciprocating clamp, and continuous belt or cleated chain.

The earliest pultrusion machines used a singular clamp, which was hydraulically operated to grip the part between contoured pads. A carriage containing this clamping unit was then pulled by a continuous chain, which was driven by a variable-speed reversible drive train for a stroke of 3 to 4 m (10 to 12 ft). At the end of the stroke, the clamp released, and the clamping carriage returned to its starting point. During this return interval, the product remained stationary until the clamping and pulling cycle could be reinitiated. Because of this pull-pause sequence, this style became known as an intermittent-pull machine. Variations of this design are still found in the industry, including multiple clamping heads for multiple-cavity production.

The continuous-pull reciprocating clamp machine, which has become the most popular style, takes this concept one step farther. Its clamping, extension, and retraction cycles are synchronized between two pullers to provide a continuous pulling motion to the product. The value of using the intermittent-pull cycle with slow-cure materials or for purging die buildups is reflected in the fact that commercial reciprocating clamp machines now have intermittent pull sequences. Subtle variations exist in the use of such drive methods as direct-acting hydraulic cylinders, hydraulic motor chain drives, or recirculating ball screws. Methods of clamping can be hydraulic, pneumatic, or a mechanical wedge action. The basic prerequisite is that sufficient clamping pressure be available on a relatively short (460 mm, or 18 in.), contoured puller block that is held within the clamping envelope. In addition, sufficient thrust must be provided to the clamping unit to overcome the die resistance and to maintain a uniform pulling speed. An advantage of the reciprocating clamp system is its need for only two matched puller pads to attain a continuous pulling motion. These pads are easily changed and are generally of durable urethane-coated steel for long life.

Continuous-belt pullers have evolved from extrusion takeoff pullers, but they have been modified for higher loads. These pullers are suitable for single-cavity or multiple-cavity production when they are all of the same physical size. Even with this restriction, uneven belt wear can result in slippage of adjacent cavities. On a positive note, the contact area of the belted puller is generally longer than that found with the reciprocating clamp pullers, which allows lower unit pressures on the pultrusion. A more flexible version of the continuous-belt machine is the cleated-chain (or caterpillar) puller, which has many individually contoured puller pads attached to chain ears along the chain length. This modification allows the production of complex shapes and multiple cavities. Machine controls are used to ensure that even pressure is maintained between opposing chain pullers. The number of individually contoured puller pads can vary widely, depending on the complexity of the part. For the average part, the number of pads will vary between 12 and 60.

5.4.3.5 Cutoff Station.

Every continuous pultrusion line requires a means of cutting the product to length. Many systems employ manual radial arm saws or pivot saws on a table that moves downstream with the product flow. More sophisticated automatic cutoff saws are found on commercial machines; this eliminates the need for operator attention. Both dry-cut and wet-cut saws are available, but

regardless of design, a continuous-grit carbide- or diamond-edged blade is used to cut pultruded products. Aramid-reinforced products present a special cutoff problem because of the toughness of the fiber. The use of conventional blades results in jagged edges and delamination. A suitable alternative is still being sought for these composites.

5.5 BRAIDING.

Braiding is a textile process that is known for its simplicity and versatility. Braided structures are unique in their high level of conformability, torsional stability, and damage resistance. Many intricate material placement techniques can be transferred to and modified for composite prepreg fabrication processes. The extension of two-dimensional braiding to three-dimensional braiding has opened up new opportunities in the near-net shape manufacturing of high damage tolerant structural composites.

In the braiding process, two or more systems of yarns are intertwined in the bias direction to form an integrated structure. Braided material differs from woven and knitted fabrics in the method of yarn introduction into the fabric and in the manner by which the yarns are interlaced.

Braiding has many similarities to filament winding. Dry or prepreg yarns, tapes, or tow can be braided over a rotating and removable form or mandrel in a controlled manner to assume various shapes, fiber orientations, and fiber volume fractions. Although braiding cannot achieve as high a fiber volume fraction as filament winding, braids can assume more complex shapes (sharper curvatures) than filament wound preforms. The interlaced nature of braids also provides a higher level of structural integrity, which is essential for ease of handling, joining, and damage resistance. While it is easier to provide hoop (90°) reinforcement by filament winding, longitudinal (0°) reinforcement can be introduced more readily in a triaxial braiding process. In a study performed by McDonnell Douglas, it was found that braided composites can be produced at 56% of the cost of filament-wound composites because of the labor savings in assembly and the simplification of design. By using the three-dimensional braiding process, not only can the intralaminar failure of filament-wound or tape laid up composites be prevented, but the low interlaminar properties of the laminated composites can also be prevented.

Coupled with the fully integrated nature and the unique capability for near-net shape manufacturing, the current trend in braiding technology is to expand to large-diameter braiding; develop more sophisticated techniques for braiding over complex-shaped mandrels, multidirectional braiding, or near-net shapes; and the extensive use of computer-aided design and computer-aided manufacturing (CAD/CAM).

The following section describes basic terminology, braiding classifications, and the formation, structure, and properties of the braided structures, with specific attention to composites.

5.5.1 Braiding Classifications.

One of the most attractive features of braiding is its simplicity. A typical braiding machine essentially consists of a track plate, spool carrier, former, and a take-up device. In some cases, a reversing ring is used to ensure uniform tension on the braiding yarns. The resulting braid geometry is defined by the braiding angle, θ, which is half the angle of the interlacing between yarn systems, with respect to the braiding (or machine) direction. The tightness of the braided structure is reflected in the frequency of interlacings. The distance between interlacing points is known as pick spacing. The width, or diameter, of the braid (flat or tubular) is represented as d.

The track plate supports the carriers, which travel along the path of the tracks. The movement of the carriers can be provided by devices such as horn gears, which propel the carriers around in a maypole fashion. The carriers are devices that carry the yarn packages around the tracks and control the tension of the braiding yarns. At the point of braiding, a former is often used to control the dimension and shape of the braid. The braid is then delivered through the take-up roll at a predetermined rate. If the number of carriers and take-up speed are properly selected, the orientation of the yarn (braiding angle) and the diameter of the braid can be controlled. The direction of braiding is an area of flexibility, because it can be horizontal, vertical from bottom to top, or inverted. When braiding over large mandrels, horizontal braiding is required.

When longitudinal reinforcement is required, a third system of yarns can be inserted between the braiding yarns to produce a triaxial braid. If there is a need for structures having more than three yarn thickness, several layers (plies) of fabric can be braided over each other to produce the required thickness. For a higher level of through-thickness reinforcement, multiple track braiding, pin braiding, or three-dimensional braiding can be used to fabricate structures in an integrated manner. The movement of the carriers can follow a serpentine track pattern or orthogonal track pattern by means of a positive guiding mechanism and/or Jacquard-controlled mechanism (lace braiding). Jacquard braiding uses a mechanism that enables connected groups of yarns to braid different patterns simultaneously. For simplicity, and to be consistent with the literature in the composite community, the dimensions of braided structures are used as the criteria for categorizing braiding. Specifically, a braided structure having two braiding-yarn systems with or without a third laid-in yarn is considered two-dimensional braiding. When three or more systems of braiding yarns are involved to form an integrally braided structure, it is known as three-dimensional braiding.

5.5.2 Two-Dimensional Braiding.

The equipment for two-dimensional braiding is well established worldwide, but especially in Germany. One of the oldest braiding machine manufacturers in the U.S. is Mossberg Industry (also known by its former name, New England Butt and now called Wardwell Braiding Machine Company), which manufactures braiders ranging from three-carrier to 144-carrier models. There are a number of braid manufacturers actively producing braided preforms and/or developing braided composites. A wide range of applications has been reported by these companies,

including medical, recreational, military, and aerospace uses. The versatility of braiding for forming complex structural shapes is well known.

The mechanical behavior of a composite depends upon fiber orientation, fiber properties, fiber volume fraction, and matrix properties. To conduct an intelligent design and selection process for using braids in composites, an understanding of fiber volume fraction and geometry as a function of processing parameters is necessary. The fiber volume fraction is related to the machine in terms of the number of yarns and the orientation of those yarns. The fiber geometry is related to the machine by orientation of the fibers and final shape.

The two-dimensional braider facilitates fabrication of net shape composite preforms. Using a mandrel, the shape is formed, and the fiber volume fraction can readily be determined by the orientation and amount of fiber used. It is quite conceivable that a 5-cm (2-in.) -diameter braid can be produced on a wide range of braiding machines ranging from 24 to 144 carriers. However, the resulting braid angle and fabric thickness would vary. On the other hand, if the braiding angle is the key requirement, then one can vary the number of plies per yarn in order to produce a 5-cm (2-in.) -diameter braid on various braiding machines. It is of interest to note that the higher the number of carriers, the wider the range of diameters that can be produced. Because of the diversity of applications of braided composites, the current trend in the braiding industry is toward larger diameter braiders.

5.5.3 Three-Dimensional Braiding.

Three-dimensional braiding is an extension of two-dimensional braiding technology in which the fabric is constructed by the intertwining or orthogonal interlacing of two or more yarn systems to form an integral structure. Well-known examples of three-dimensional braids are the diagonal, or packing, braids that are produced by the intertwining of three or more groups of yarns in a square arrangement of horn gears. Serious consideration of three-dimensional braid for composites started in the late 1960s in the search for multidirectionally reinforced composites, such as rocket motor components for aerospace applications. The Omniweave by General Electric and SCOUDID by Societe Europeene de Propulsion are examples of new developments. The mechanism of these braiding methods differs from traditional braiding methods only in the way the carriers are displaced to create the final braid geometry. Instead of moving in a continuous maypole fashion as does the square braider, these three-dimensional braiding methods invariably move the carrier in a sequential, discrete manner, which is quite suitable for adaptation for computer control.

The basic braiding motion includes the alternate X and Y displacement of yarn carriers followed by a compacting motion. The formation of shapes is accomplished by the proper positioning of the carriers and the joining of various rectangular or annular groups through selected carrier movements.

The three-dimensional braiding system can produce thin and thick structures in a wide variety of complex shapes. By proper selection of the yarn bundle sizes, the dimension of these structures can be as thick as desired. Fiber orientation can be chosen, and 0 degree longitudinal reinforcements can be added as desired. Although this system is not yet fully automated, extensive analytical research has been done in this area, and comprehensive models have been developed relating final shape to manufacturing processes. Considering the potential for near-net shape formation of high damage resistant composites, extensive developmental programs have been carried out at Drexel University and by Atlantic Research Corporation. Examples of these structures are I-beams, hat sections, rocket motor exit cones, and marine propellers.

The development of a processing science base for three-dimensional braided fabrics for composites consists of two basic components: quantification of fabric geometry and determination of fiber volume fraction. With these components and knowledge of fiber and matrix properties, a fabric can be formed to specification. The mechanical analysis of a composite depends upon the fabric properties that can be quantified using the properties, architecture, orientation, and volume fraction of the fiber.

5.6 NEWER (NONLAY-UP) MANUFACTURING METHODS.

A fiber preform and in situ resin impregnation approach to manufacturing conventional and advanced composite structures can offer significant advantages over traditional, time-consuming methods of hand lay-up. Of course, this depends on application requirements such as contour, thickness, and durability.

This approach, which emerged from the textile industry, involves the assembly of dry, unimpregnated continuous fiber preforms for subsequent injection or infusion of the matrix resin. It was the increasing use of continuous fiber reinforced composite materials in aerospace, automobile, and other weight-critical applications that generated interest in improving both their durability (for more demanding applications) and cost effectiveness compared to conventional metallics. This section describes the manufacturing processes for assembling and impregnating oriented, unidirectional graphite fiber preforms by the resin film infusion/pressure molding and resin transfer molding (RTM) processes.

5.6.1 Preform Materials and Assembly.

Fabric is the starting point for most preforms because it positions the reinforcing fibers in principal directions. Preform fabric can be any one of the conventional fabrics, such as plain weave, five- or eight-harness satin, unidirectional or multidirectional knitted, or bias weave. Fabric selection is dependent on the final properties desired in the component as well as on the configuration of the manufactured part (simple versus complex contour). As the structural performance required of a component increases, the use of noncrimped fabric (that is, knitted and woven unidirectional fabrics) becomes more desirable because of the increase in tensile and

compression performance. Increased performance is gained by eliminating the kinks within fiber bundles that result from the over-and-under construction of the woven materials.

Predominant starting materials for preform fabrics are fiberglass, carbon, and aramid fibers. Silicon carbide, aluminum oxide, boron, borsic (boron fibers with a silicon carbide coating), quartz, and others are also used in specific applications. As with all composite structures, selecting the reinforcing fiber for the preform depends on the end-use characteristics desired in the composite structure.

The reinforcing thread material used to hold the preform together can be virtually any fiber that will endure the sewing process. The fibers with higher tenacity, such as aramid and polyester, will obviously cause fewer complications than will the more brittle higher-performance fibers, such as graphite, glass, or ceramic.

The operation that requires the most thread strength is the actual stitching of the dry laminate when the needle penetrates the preform to complete the stitch. A brittle thread will often shear at the needle eye, a tendency that may depend on needle eye diameter, feed rate, and type of stitch used, such as the lock or chain stitch. Depending on the application, a material with maximum tenacity should be chosen to minimize complications in the stitching process.

5.6.2 Assembly.

The desired mechanical and thermal performance of the composite structure is established during the preform design process. Preform assembly converts individual fabrics into the multilayered configuration specified by the composite designer. The fabric layers are assembled into the final configuration in a process analogous to a prepreg lamination operation. Fabric layers are placed in a predetermined orientation by rotating the principal axes of the fabric layers or by using a multidirectional fabric. The assembly process can be automated by using broad goods spreaders and robotic placement.

In most applications, particularly in aerospace composite structures in which weight is critical, buildups are used in strategic locations to handle high, localized loads. The buildup is usually an individual preform manufactured in a separate operation. Buildups generally consist of additional layers of fabrics that are sandwiched within the principal preform layers during the assembly process. Fixturing ensures proper buildup location and stitching in place prevents shifting during impregnation and cure.

Critical material parameters, such as the reinforcement area's weight and fiber orientation, are maintained by using assembly fixturing to lock the fabric in place mechanically prior to the stitching operation and to minimize fiber distortion during subsequent handling operations.

The final operation in preform assembly is the stitching process. Stitching mechanically fixes the final shape of the preform and constrains fiber movement during resin impregnation. In addition

to serving as an assembly material, stitching also may be incorporated as a reinforcement in the Z-axis direction. Stitching with structural thread (fiberglass, aramid, or carbon) has been shown to improve compression after impact by 80%. Actual improvement in Z-direction properties depends on the spacing, pitch (the amount or volume), and type of fiber used as the stitch thread.

Depending on the component configuration and the type of stitch thread, equipment can range from standard industrial sewing machines to fully computerized equipment with a contour capability. Stitching with high-modulus, low-elongation fibers such as carbon requires specially modified equipment to prevent fiber breakage during the stitching process. Whenever a stitching operation is to be performed, it is advantageous to work with a fiber preform that is free of resin or heavy binders because their presence limits the mobility of the fiber during needle penetration and results in a large number of fractured preform and thread fibers.

Three-dimensional preforms are being used increasingly. Three-dimensional weaving, tubular braiding, and rectangular braiding are the most common methods currently employed. These processes form a network of fibers that result in some quantity of fiber being oriented through the thickness. Three-dimensional preforms are generally used on pails having a constant cross section that must handle a significant out-of-plane load and/or that require a high degree of damage resistance. Currently, three-dimensional preforms are predominantly used in carbon-carbon composite structures.

5.6.3 Resin Injection.

Resin film infusion is a technique for impregnating preforms with hot-melt resin systems, which are resins that are solid at room temperature. These resins include typical aerospace-grade epoxies, bismaleimides, and polyimides.

Preforms are loaded into a holding fixture to stabilize the preform during the infusion process. Resin, in film form, is positioned uniformly onto the preform. The starting ratio of fiber to resin weight is nominally held to 50% resin and 50% fiber. This may vary depending on preform thickness, contour, and subsequent processing method. During the molding operation, the final ratio of fiber to resin weight for fabrics is established at 32% to 35% resin and 68% to 65% fiber for aircraft applications.

Actual impregnation occurs in a heated vacuum chamber. The preform, with resin applied, is positioned in the chamber. Heat is then transmitted to the preform and resin by means of infrared radiation. A vacuum is applied during the impregnation cycle to remove entrained air and volatiles from the filmed resin. Preform impregnation occurs through capillary wetting of the preform as the viscosity of the resin decreases. During impregnation, the vacuum is cycled to prevent excessive resin bubbling and provide a mechanical pumping action to complement capillary wetting. At the end of this cycle, the resin is not cured, but it is in an advanced B stage. In the resin film infusion/pressure molding process, the final sequence is the molding operation itself, which establishes the final shape of the composite structure, fixes the proportions of fiber

and resin, cures the resin, and provides the composite structure with its designed mechanical and thermal properties.

The pressure molding process uses integrally heated, matched surface tooling in conjunction with an autocomp vessel to perform the final cure. Positive-stop surfaces within the tool establish the final part thickness. Resin-to-fiber ratio is maintained by controlling the amount of fiber in the cavity and the final thickness of the part. Excess resin is allowed to flow into resin traps incorporated around the perimeter of the part.

The manufacturing steps for the molding operation are as follows: The tool is prepared by removing any residual material from previous processing and applying a release coat to the molding surface to prevent bonding of the part to the tool. The impregnated preform is placed on the tool, and the remaining tool pieces are installed. The entire tool is inserted into the vessel, which has a permanent, reusable, internal vacuum bag that envelopes the tool as it is inserted. Vacuum is drawn at the beginning of the cure cycle to remove air from the mold cavity and the impregnated preform. Pressure is applied (590 to 690 kPa, or 85 to 100 psi) as the cure progresses and is maintained throughout the cycle. Once the desired level of cure is achieved, the part is cooled under pressure and removed from the tooling.

5.6.4 Resin-Transfer Molding (RTM).

In resin-transfer molding (RTM) or resin-injection molding (RIM), a mold is loaded with reinforcement material, then closed, and resin is injected into it. The mold with the preform in it is often put under vacuum. This removes entrapped air from the reinforcement and speeds the RTM process. The reinforcement material is wetted out by the pressure of the injection.

This method has some similarities to other composite and nonreinforced plastic manufacturing methods. For example, the method of loading the reinforcement is similar to preform molding, but in preform molding, the resin is introduced into an open mold. Pressures are also much higher in preform molding. Transfer molding, from which this method gets its name, is a process in which a thermoset resin is injected into a closed mold. However, in traditional transfer molding, reinforcement is not incorporated. One further comparison is with reaction-injection molding which is a process in which two reactive resin components are mixed and then injected into a closed mold. Large, nonreinforced parts are often made by the reaction-injection molding (RIM) process. RTM is a logical extension of several other processes to fill a specific need for improving the productivity of making composite parts. RTM has been used in the automotive industry and is the process used for manufacturing body panels and other parts.

Most standard reinforcement materials can be used, but fiberglass, carbon, and aramid are the most common. One requirement on the form of reinforcement is that it retains its shape during injection. Therefore, the reinforcements are generally stitched or bonded together. Preforms are common. In certain areas reinforcement buildups are also easily included. Inserts of various

types, such as screw receptacles and ribs, can be easily placed in the open mold at the same time as the fibrous reinforcement.

5.6.4.1 Resins and Pumping Equipment.

Most of the standard composite resins can be used in RTM, but the viscosity must be low enough for the fibers to be easily wetted. The resin should also have a pot life of about 2 hours so that injection can be slow (for wet-out) without having the resin gel. Polyester and epoxy resins are the most common.

A catalyst, or curing agent, is kept separate from the resin to allow the use of highly reactive resin-catalyst systems for fast cures and to facilitate storage of the materials. Using heated flow tubes if necessary, the resin and catalyst are pumped simultaneously through a static mixer and then into the tool, which is maintained at a temperature that allows sufficient time to fill the mold before the resin gels. One or more ports are located on the tool to bleed the air out as the resin fills the cavity and to indicate when the cavity is filled. Vacuum, vent, and nitrogen back pressure can be maintained at each port, if desired. Vacuum is used to evacuate the tool as the cavity is being filled and to facilitate resin flow into the tool. The nitrogen back pressure is applied after the cavity has been filled to stop the resin flow through the tool, keeping the matrix under pressure and preventing void growth in the laminate.

The critical factors in selecting a resin are minimum viscosity and the length of time and temperature the resin will remain at this minimum viscosity (pot life). In general, a maximum viscosity of 1 to 3 P (100 to 300 cP) is desired for the matrix to impregnate the reinforcement properly. This may vary with fiber volume. The time required for the resin to remain at this viscosity depends on several factors: fiber volume, fabric type, wet-out area (or area of reinforcement to be impregnated), and tooling configuration (number and location of injection and vent ports). The resin may be capable of maintaining the required minimum viscosity at room temperature, or it may require a slight application of heat to achieve adequate flow. Applying heat will also accelerate the cure and reduce the time at minimum viscosity.

The resin pumping system can be much like the type required for spray-up molding. However, much simpler systems with only a ram or an airline to insert the resin have also been used. Care should be taken to maintain good temperature control on the pumping/inserting mechanism to prevent premature gelation.

5.6.4.2 Mold Design for RTM.

The design of the mold is the most critical factor in successful resin-transfer molding. The mold must be constructed so that resin reaches all areas and concentrations are approximately the same throughout. This resin movement must be accomplished within the time allowed before the onset of gelation. Additionally, the resin-injection process should not cause movement of the

reinforcement and should be done at low pressures so that the mold will maintain its shape without resorting to massive backing methods.

Mold designers have learned that RTM molds must be vented to allow the air within the mold to be pushed out by the resin. Venting is also common in compression and transfer molds. Though vents allow air to escape, they are too narrow to allow the thicker resin to flow out. The mold should also have good temperature control. Even molds intended for room temperature cured resins should be well insulated so that the environmental conditions do not change the gel times and viscosity of the resin. Some molds are heated or designed to go into ovens to effect curing at higher temperatures.

RTM molds are usually made from metal; however, if warranted, they can be made of other materials such as composites. Also, the low-pressure requirements of RTM allow the use of many more mold materials than would compression molding. The choice between metal molds and composites is chiefly one of volume and temperature. High volume and high temperatures dictate metal molds.

Sometimes the mold must be backed up in order to maintain its shape. Backup can be done with ribs or by simply adding mass (such as cast aluminum). Closure of the mold is also important since the mating of the mold surfaces against a gasket is often the method of keeping resin from squirting out. Therefore, alignment pins are usually used to ensure that the mold halves meet properly.

5.6.4.3 Uses for RTM Parts.

Manufacturing of large parts is the primary use for RTM. The reason is that production volume and efficiency are higher for RTM than for lay-up. Typical parts would include machine cabinetry, solar collectors, snowmobiles, bathtubs and shower enclosures, airplane wing ribs, hatch covers, car bodies, and bus shelters. Advantages of RTM:

- Very large and complex shapes can be made efficiently and inexpensively.
- Production times are much shorter than lay-up.
- Clamping pressure is low compared to matched metal molding.
- Surface definition is superior to lay-up.
- Inserts and special reinforcements can be added easily.
- The skill level required of the operator is low.
- Many mold materials can be used.
- Parts can be made with better reproducibility than with lay-up.
- The worker is not exposed to chemicals and vapors as he would be with lay-up.

The mold design is critical and requires great skill.

- Properties are equivalent to matched-die molding (assuming proper fiber wet-out, etc.) but are not generally as good as with vacuum bagging, filament winding, or pultrusion.

- Control of resin uniformity is difficult. Radii and edges tend to be resin rich.

- Reinforcement movement during resin injection is sometimes a problem.

5.6.5 Inspection.

Nondestructive inspection of a cured composite laminate is commonly preformed using an ultrasonic signal to detect voids or delamination. This can be accomplished manually by passing a signal through a transducer, a fluid couplant, the laminate, and then detecting a reflection off the back surface of the laminate (A-scan). Other methods use water as the medium for the ultrasonic signal. Although these methods may be used to inspect an impregnated, stitched laminate, a discontinuity will appear at each stitch in the form of an attenuated, or unreflected, signal. This occurs because the fibers in the out-of-plane direction absorb the signal and do not reflect it as the surrounding area of the laminate does.

5.7 FABRICATION USING HIGH-PERFORMANCE THERMOPLASTICS.

Because of the high melting points of these resins, high-performance thermoplastics cannot be processed using typical plastics processing equipment unless this equipment has been upgraded to handle higher temperatures and pressures. Many of the typical thermoset processes, such as filament winding and pultrusion (discussed later in detail), are also difficult to apply to high-performance thermoplastics because of the high viscosity of their melts, for example 104-101 poise versus 10 poise for noncured epoxy (molasses is about 101). This high viscosity in thermoplastics makes wet-out of the reinforcement very difficult.

Increasing the temperature lowers the viscosity but can cause decomposition before sufficiently low viscosities are reached. Thus, high consolidation pressures are commonly employed. Another method to alleviate this wet-out problem is to take advantage of the shear sensitivity of some thermoplastics. These resins are non-Newtonian and undergo shear thinning. Therefore, reinforcements can be impregnated by forcing the resin and fibers through a die at high temperature under conditions that create high shear.

Another approach to making laminates or other shapes with a thermoplastic matrix is to first shape the thermoplastic into fibers and intermingle these fibers with the normal reinforcement fibers. When these cofibrous materials are pressed and heated, the thermoplastic fibers melt and coat the reinforcement fibers. A modification of fiber commingling is to intermingle reinforcement fibers or fabric with thermoplastic resin powder. The result is a drapeable prepreg material with

the potential for easier processing. The melt viscosity and processing pressure is extremely critical in achieving good fiber wet-out in these materials.

Other methods which improve the wet-out characteristics of thermoplastics involve the use of solvents or plasticizers. The limited solubility of the thermoplastics and the added difficulty in removing the solvent or plasticizer makes this approach difficult; nevertheless, some success has been found. However, the removal problem can be avoided if a reactive solvent or plasticizer is used so that it is incorporated into the final structure of the material.

Another fabrication problem is due to the stiffness of prepregs made from high-performance thermoplastics. These prepreg materials are generally so stiff that they will not conform to molds or other contours. However, they can be softened by using a heat gun or soldering iron to induce tack (stickiness) and shape them; this technique is generally limited to small applications.

6. PROCESSING.

6.1 AUTOCLAVE PROCESSING.

For curing the composite or adhesive in many assemblies, higher pressure than vacuum may be required (15 to 100 psi or higher for thermoplastics). This is obtained by use of an autoclave. Positive pressure can be added to the vacuum cure to create an accumulative pressure or the vacuum pressure can be released to the outside atmosphere to allow only positive pressure to be applied to the assembly. Due to the nature of some adhesives, a vacuum must not be maintained during the cure cycle. Positive pressure is accomplished by pumping compressed gas into the autoclave. Thermocouple wire connections and vacuum hose connections are available and are passed through the autoclave wall where they are connected to automatic controlling and/or recording equipment. A typical autoclave is shown in figure 33.

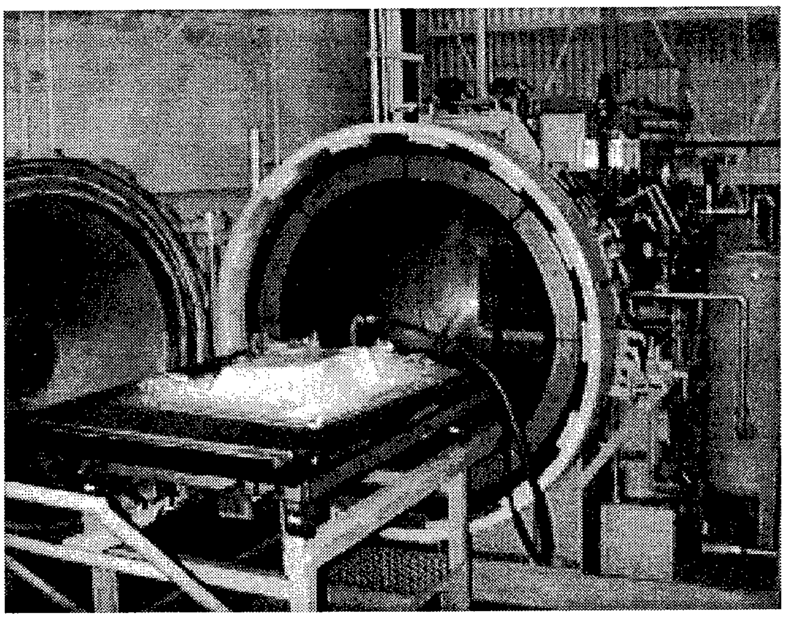


FIGURE 33. AUTOCLAVE

Autoclave processing utilizes a pressure chamber to apply heat and pressure to the composite lay-up during the consolidation/cure cycle. Autoclave curing is the most common method of fabrication utilized in the aerospace industry to produce composite structural parts. The autoclave process is an economical method for the fabrication of extremely high-quality parts and accommodates a large variety of part configurations. The primary disadvantage of autoclave processing is the high cost of initial acquisition of an autoclave and the high recurring operating costs. The advantage is the use of simple, one surface tooling to produce parts with complex configurations and very large sizes.

The type of prepreg material and the part configuration govern the pressure and temperature requirements. Epoxy matrix composites typically use autoclave cure cycles with 85-100 psi pressure and 350°F temperatures. The autoclave is generally provided with automatic programmable controllers which monitor and maintain the required heat-up and cool-down cycles. The temperature increases in a stair-step fashion. The temperature dwell points allow volatiles to be removed from the matrix prior to gelation and flow condition the prepreg material for the final cure. The vacuum applied to the bay surrounding the part lay-up is also controlled. The vacuum is discontinued after the initial temperature increase to prevent excess resin flow.

The molds or tools used in an autoclave are usually made of metal or composite and must, of course, withstand the forces of the autoclave. The autoclave provides pressure beyond that available with vacuum only and, therefore, gives greater compression and void elimination. Autoclave tools are more permanent than the typical lay-up mold. Autoclaves allow the simultaneous imposition of heat and pressure (and vacuum if a vacuum line is led directly to the part). The major difficulty with autoclaves is the high capitalization cost which results because autoclaves are pressure vessels and must, therefore, pass stringent pressure code regulations. However, because many parts can be cured simultaneously in an average autoclave, labor and cure costs on a per part basis need not be extremely high.

The autoclaves used in aircraft part fabrication are generally heated by convection. Natural gas or propane is burned, and a heat exchanger is used to provide heat internally in the autoclave. Electric and steam heated autoclaves are also available. Temperatures up to 800°F are possible using this technique. The size of the autoclave is highly variable. Many manufacturers have autoclaves in the range of 12 to 15 feet in diameter and 45 to 50 feet in length. The pressure capacity of these autoclaves is generally limited to 200 psi. A schematic of an autoclave is shown in figure 34.

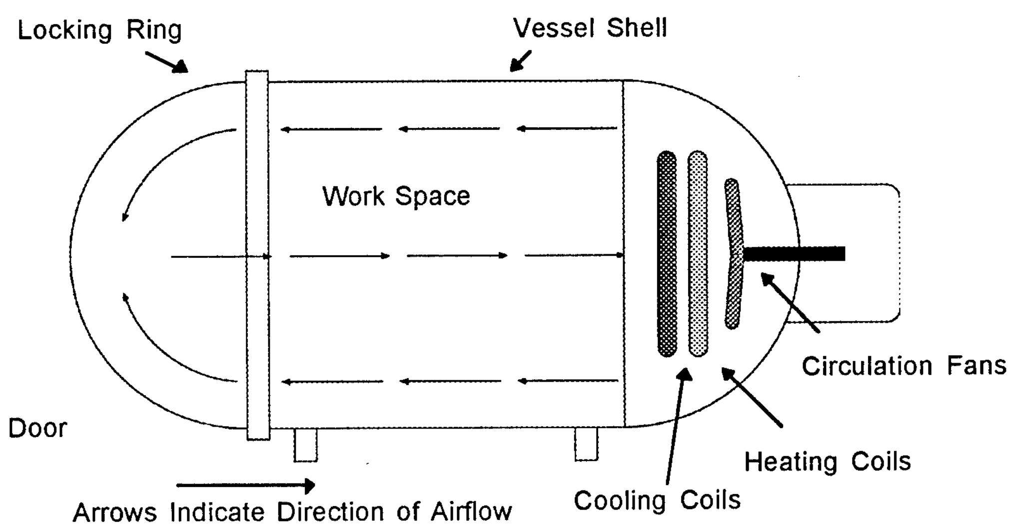


FIGURE 34. CONVECTION AUTOCLAVE SCHEMATIC

Autoclaves can be purchased as large as 25 feet in diameter and 100 feet in length. The concerns in purchasing and operating autoclaves are the uniformity of the heat flow to avoid thermal stresses, closure integrity, insuring that the insulation is good, obtaining good and easy-to-operate controls, and insuring that fires do not occur from the high temperature and pressure. An inert gas is usually put into the autoclave to reduce the fire danger.

The type, composition, and size of the tooling can affect the cure because the heat-up rates of the tooling can vary widely. In some cases, the tooling is heated independently to reduce the problem of variable heating and to accelerate the cure by quickly getting the entire assembly to cure temperature. Special tooling may be required in autoclave curing to prevent bag failure, collapse of parts, or crushing of honeycomb details.

The net result is that curing in an autoclave produces a part that is superior to one produced through nonpressure curing. Therefore, an autoclave is used extensively for making high-performance aerospace parts. It is, in fact, the principal method employed for producing very complex parts.

6.1.1 Autoclave Curing.

An autoclave system used for curing composites should have the following minimum requirements:

- Sufficient thermal input source to provide quick temperature changes from one temperature to the next during the cure cycle. In general the autoclave should be capable of operating through a temperature range of room temperature to 350°F (177°C). If additional temperature is required for postcuring it is more economical to postcure the parts in an oven. A typical cure temperature cycle is shown in figure 35.

- The autoclave must include a means for circulating the gas inside since temperature in the curing area should be maintained at a specific curing temperature with a tolerance of ±15°F (± 8.3°C).

- A high-capacity pressurization system is required to pressurize the large volume of the autoclave quickly. In many installations CO_2 or N_2 is used as the pressurizing medium because of their fire-retardant characteristics. Both N_2 and CO_2 require a large storage pressure vessel; however, because of the cost of CO_2, it is usually recycled. The pressure used during cure usually does not exceed 200 psi (1400 Pa).

- An adequate vacuum system is required to maintain vacuum pressure on the parts before cure and during cool down after cure. During cure the pressure is maintained on the parts by the autoclave gas.

- The autoclave should provide an automatic recording system for a permanent record of pressure and temperature for each cure cycle.

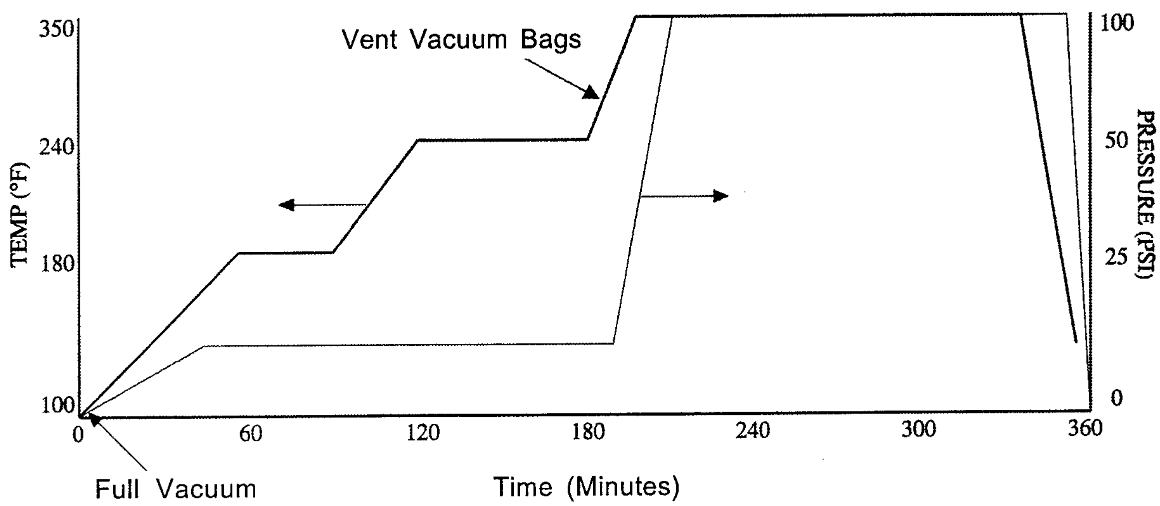


FIGURE 35. AUTOCLAVE CURE CYCLE

<u>6.1.2 Steps in Autoclave Curing</u>.

The following general steps are required for curing composites in an autoclave.

- Parts that have the same cure cycle are placed on the same dolly.

- The dolly is placed in an autoclave, and vacuum hoses are connected so the vacuum pressure is registered on gages outside the curing chamber. This checks the parts for vacuum leaks.

- Doors are closed, and the cure cycle begins.

- For autoclave curing, the pressure and heat are increased as required by the cure cycle.

- After the particular standard cure cycle has been completed, the air pressure in the autoclave is released. The doors of the autoclave are opened slightly to help cool the part.

- All parts should be cooled below 150°F (66°C) while still under vacuum pressure to minimize thermal shock and warpage.

Many parts that have been laid up, bagged, and cured correctly are rejected because they are damaged while being removed from the tool. The bagging materials and parts must be removed carefully! Some typical cure cycles for different matrix materials are shown in table 8.

TABLE 8. TYPICAL CURE CYCLES FOR STRUCTURAL PARTS

Resin Type	CURE CYCLE TEMPERATURE			POSTCURE CYCLE TEMPERATURE		
	°F	°C	Time, h	°F	°C	Time, h
	Pressure 10-25 lb/in^2 (69-172kPa)					
Epoxy (medium temperature)	200 250	93 121	1 0.5	250 300 350	121 149 177	0.5 0.5 2
Epoxy (high temperature)	200 300	93 149	1 1	200 300	93 149	0.5 1
	Pressure 10-45 lb/in^2 (69-310kPa)					
Phenolic	200 250 275	93 121 135 ±	0.75 0.5 0.5	300 350 350 425 460 520 620	149 177 177 218 238 271 327	0.5 2 4 4 4 4 4
Silicon	350	177	1	200 250 300 350 400 480	93 121 149 177 204 249	16 2 2 2 2 16

± The cure cycle for polyimide consists of raising from room temperature to 350°F (177°C) at 140 ±20 min. holding at 350°F (177°C) for 120 ±15 min. and cooling under vacuum to 150°F (66°C).

6.2 VACUUM BAG CURES.

Vacuum bag processing utilizes a flexible film or rubber bag that covers the part lay-up. The bag permits the evacuation of air to apply atmospheric pressure. The use of vacuum bag pressure alone as a consolidation technique is widespread and second only to autoclave processing. The primary limitation of vacuum bag processing is the limited pressure that can be applied. Autoclave processing has the flexibility of applying much higher pressures that are required to consolidate many sophisticated engineering materials.

The bag, to be useful in vacuum bag processing, must be capable of removing volatiles during cure in a convection oven and have sufficient strength to sustain application of a pressure of one atmosphere which is adequate for most materials.

When individual plies of prepreg material are hand-formed to the lay-up tool a certain amount of voids exist between layers. By applying a flexible membrane over the tool and sealing this material to the tool, a vacuum can be drawn on the plies, resulting in a pressure of up to 15 psi on the lay-up.

The requirements for proper bagging are

- The bag must be impervious to air passage.
- The bag must uniformly apply the cure pressure.
- The bag (and the tooling surface) must not leak under oven conditions.
- A good, high-capacity vacuum path must be provided to evacuate air from between the bag and the tool.

Primarily, two bagging methods are presently in use. The most common method uses a disposable bag made of nylon or Kapton polyimide film. The other method involves the use of silicone rubber bags that are reusable. The advantages and disadvantages of the two bagging systems are presented below:

- A reusable bag is usually molded to the particular part configuration resulting in less labor time required to bag the part.
- A disposable bag requires extensive hand labor to remove wrinkles and prevent the bridging effects that can cause areas of the lay-up to contain voids.
- A reusable bag requires an exterior framework to clamp the bag in place. This requires a more complex tool than is required for the disposal bag method.
- Disposable bags are more susceptible to pin hole leaks and edge sealing problems than the reinforced reusable bags.

A rack of bagging material is shown in figure 36.

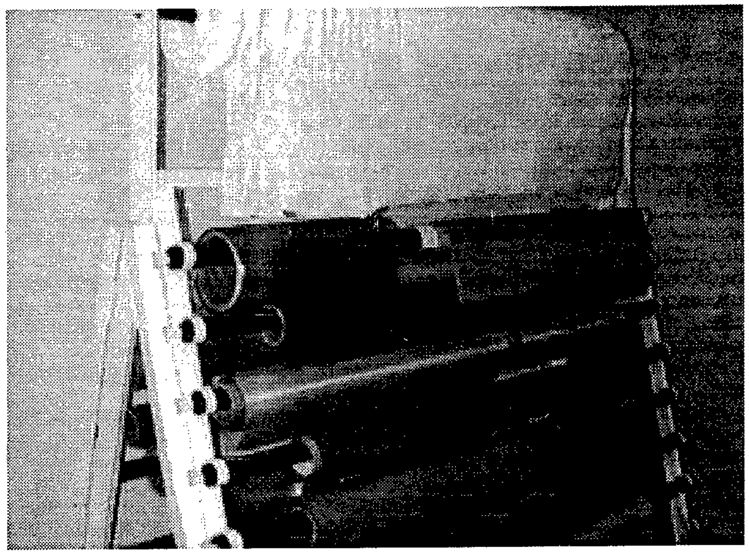


FIGURE 36. RACK OF BAGGING MATERIALS

6.3 BAG SEALERS.

Bag sealers are used to hold the vacuum and pressure plastic film bag in place without leakage during the cure cycle. Those most generally used are listed below.

- Zinc Chromate Sealing Compound No. 5144 (Schnee-Morehead Chemical)
- Butyl tape (PTI)
- 782.9 Grey, 787.9 Red (Presstite Engineering Co.)
- G.S. 43 or 213 (General Sealants)
- Foster 9B2 (MIL-P-8116) (Foster Co.) for fiberglass parts only

6.4 BAG FILM.

Bag films are applied over an assembly being bonded to separate the assembly from the applied pressure. The films most commonly used are listed below.

- PVA (Reynolds Co.)
- Mylar (DuPont)
- Nylon
- Tedlar 200 (DuPont)
- SG40TR (PVF) (DuPont)

Nylon films are primarily used in laminate fabrication and bonding application because of their durability and they can also withstand greater pressure and heat. More importantly during cure, no fumes or residues are given off by the film. Nylon films are self extinguishing and have indefinite shelf life. Nylon films are available in various widths, tubing, and bags.

6.5 HEATING.

Most vacuum bag processing is cured in ovens. Various size ovens are used to cure most thermoset composites and adhesives. All ovens circulate hot air and are equipped with exterior venting. Ovens heated using gas or electricity are air cooled by opening vents. Each oven is equipped with vacuum outlets for cure requirements. Each oven is monitored by chart type recorders that record time and temperature; for example, each graph must receive an inspectors stamp at the start and at the completion of the cure. The oven cannot apply pressure to the part. An oven with a tooling rack is shown in figure 37.

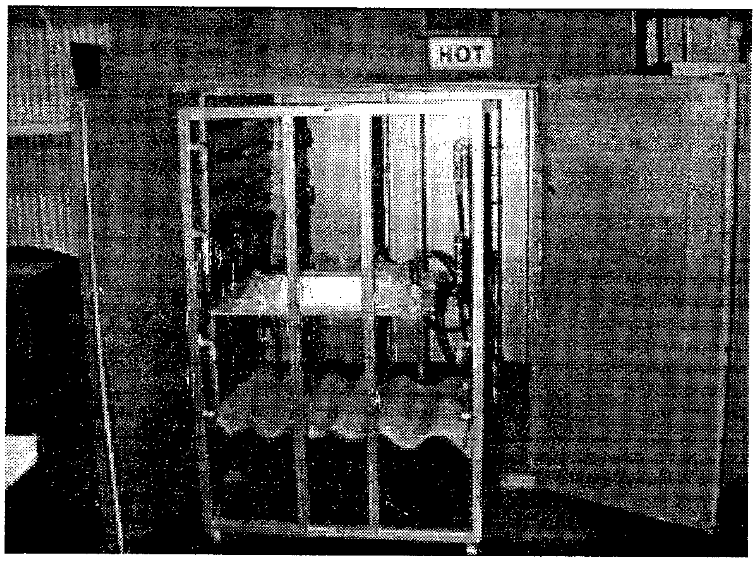


FIGURE 37. OVEN WITH TOOLING RACK

6.6 BAGGING TECHNIQUES.

For vacuum bag processing, the bags are used to evacuate the air from the laminate and to generate the atmospheric pressure required for compaction over the mold. For autoclave processing, the bags serve to contain the compacting gases during the cure. If the pressures within the bag are not reduced from those applied to the bag, the membrane remains inert and there is no compaction. Bleed-out systems are devised to maintain reduced pressures within the bag's contents. As long as the pressure within the bag remains reduced, the compacting gases bear on the bag as it presses against the lay-up.

The requirements for the pressure applications include the following.

- Consolidation of successive plies
- Completion of the fiber impregnation with the resin
- Elimination of the void nucleating volatiles, reaction by-products, and trapped air
- Reduction of the excess resin in the lay-up

Bagging is, as the word implies, installing a leak-proof seal of nylon material over the entire assembly.

When a vacuum bag is installed on a tool, trapped air is evacuated from the core cells and bondable surfaces. By drawing a vacuum, the assembly is held down against the tool surface firmly so that uniform autoclave pressure may be applied to all bondable surfaces.

The following is a general description of the bagging process. For specific steps, refer to the original equipment manufacturer's (OEM) processing specification.

The installation of thermocouple wires is made in the edge areas of the assembly. Shop drawings or specifications call out their number and location.

Protective pads of two or three thicknesses of coarse fiberglass cloth are placed over all vacuum or probe sources and taped into place. This prevents bleeder cloth from being sucked into these orifices during the cure cycle, causing incomplete air evacuation from the assembly. All tooling pins are covered with similar pads and taped into place. This prevents the protrusion of the tooling pins into the bleeder material and bag, causing a possible rupture of the bag. Any bag rupture or bond pressure loss results in fault areas in bonding referred to as voids.

Double-back tape is next applied to the bond jig at staggered intervals at the outer edge of the assembly. The entire assembly is then covered with breather material and overlapped at all abrupt contour change points and is sometimes applied in sections. This is to prevent a condition know as bridging, which results in low-pressure areas and subsequent voids. All bleeder materials must be applied in such a manner so as to not cause a bridge.

The bag sealant is laid down and pressed firmly against the tool surface around the periphery. The nylon bag is cut to fit over the tool surface, allowing ample excess for pleats to fit into contour changes. The bag is pressed down firmly onto the sealant, starting at one corner and working around the entire tool. Excess bag is drawn up and 3- to 4-inch pleats are installed every foot or so and at all contour changes on the assembly. These pleats are often referred to as ears. The ears are often taped down to the tool so as not to come loose during autoclave processing (see figure 38).

The top half of the vacuum fitting is installed. The bag is completely sealed, a light vacuum is drawn, and the bag is tucked into all contour changes, hollows, and areas of overlays. Care must be taken at this time to insure that no bridging occurs. Light vacuum (10 inches Hg) is drawn to prevent movement or crushing of the core cells.

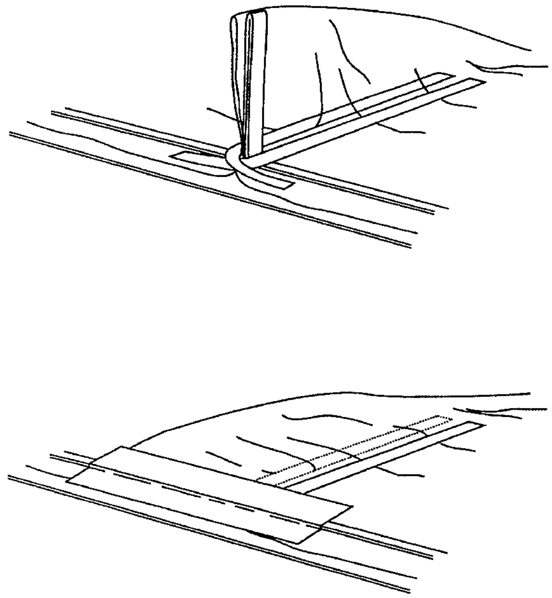


FIGURE 38. BAG EARS

The bag is then checked for leaks. Often this is done with the use of an electronic device known as a Sniffer (see figures 39 and 40). A sniffer is a sound amplified used to hear and pinpoint the location of leaks. Leaks, as detected, are resealed and special care is taken that no bridging exists (see figure 41). The bagger now identifies the assembly on the outside of the bag, using a soft felt-tip marking pen, recording the assembly number and the register number of the assembly. The bagger stamps the assembly shop order (ASO) and fills out the tool bagging card and moves the assembly into the autoclave loading area.

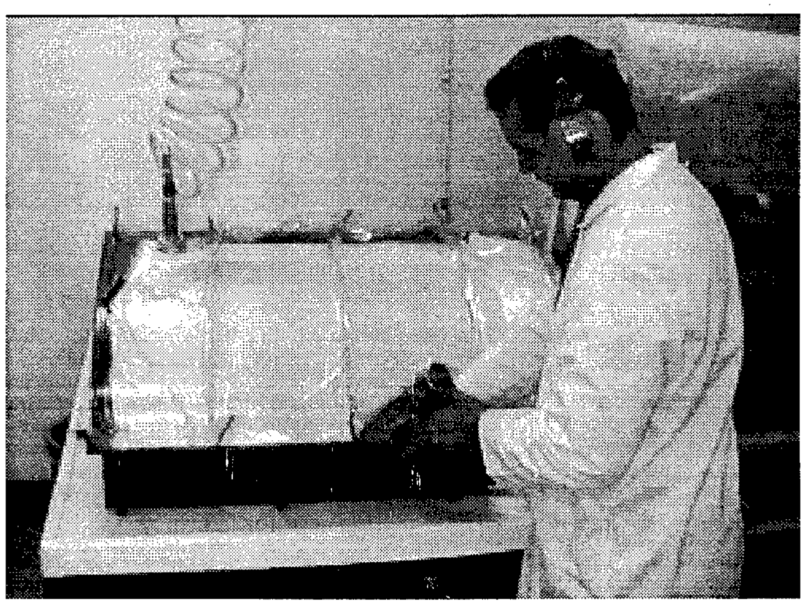


FIGURE 39. VACUUM LEAK CHECKING TOOL

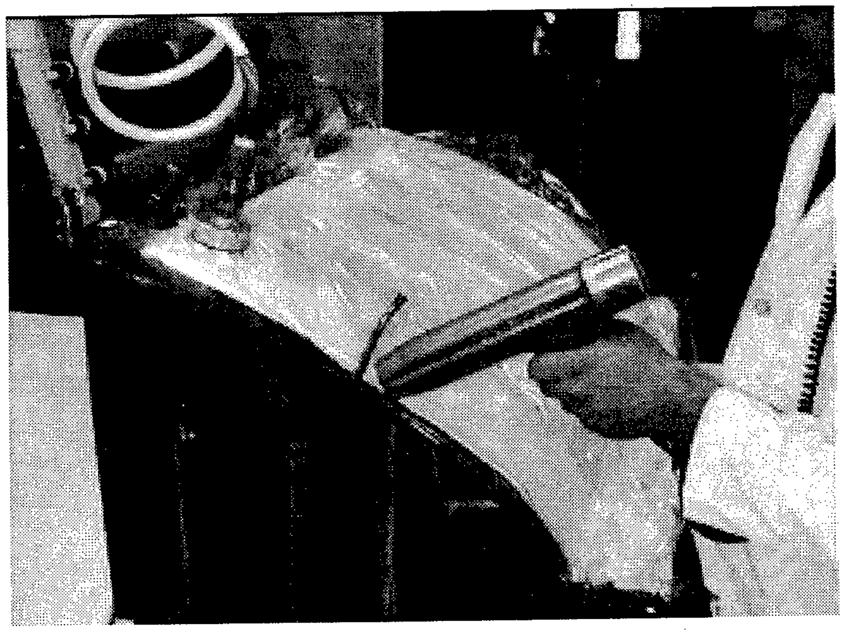


FIGURE 40. CLOSE-UP OF SOUND AMPLIFIER (SNIFFER)

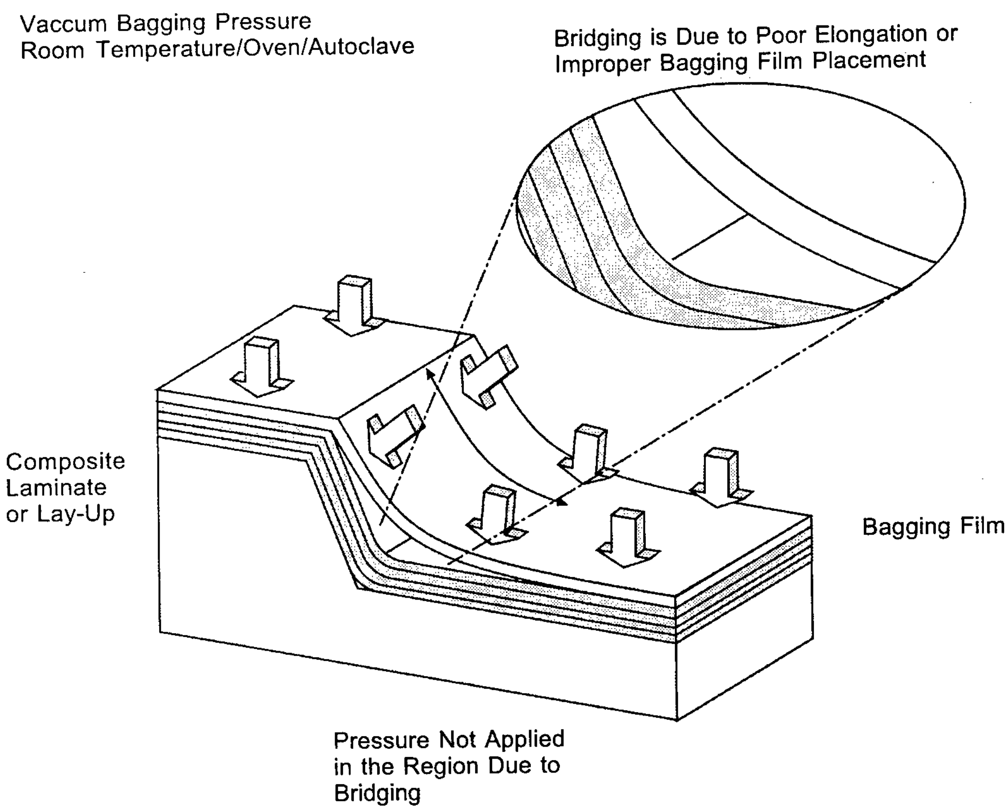


FIGURE 41. BAG BRIDGING

6.7 BLEED SYSTEMS.

The bagged lay-up includes the bleed-out system designed for the composite parts. Bagged lay-ups can be edge or vertically bled. The lay-up stacking sequence is as follows.

6.7.1 Edge Bleed.

- The surface of the mold is prepared with the release agent.
- A sacrificial ply is laid up on the prepared surface. Usually, it is a ply of 120 fiberglass fabric with a resin compatible with the resin used in the main lay-up.
- The peel ply is anchored to the sacrificial ply.
- The composite plies are oriented and laid up in the directions specified in the design and rubbed out on top of the peel ply.
- The edge bleeder is positioned at least 1/2 inch from the periphery of the lay-up and is joined to the ports of the venting system.
- Porous release fabric is laid up over the composite plies and is extended over the edge bleeder. The release fabric is made to comply to the 1/2-in. (1.3-cm) trough between the lay-up and the edge bleeder. The release fabric is trimmed so that it does not extend beyond the edge bleeder (see figure 42).
- If a self-sealing silicone rubber bag is not used, a bag sealer is applied 1/2 to 1 in. (1.3 to 2.5 cm) from the periphery of the edge bleeder.
- Special care is taken to seal the bag covering the assembly so that it will not leak.
- The bag contents are evacuated and the system is checked for leaks. All leaks are sealed.
- The bagged lay-up is ready to be cured.

This system does not provide for significant resin bleed out and provides only a partial escape of volatiles. Composites cured using this system will usually have tapered edges to a distance of about 2 in. (5 cm) from the edge of the lay-up. These are normally removed from the cured composite and sometimes are used for quality control tests.

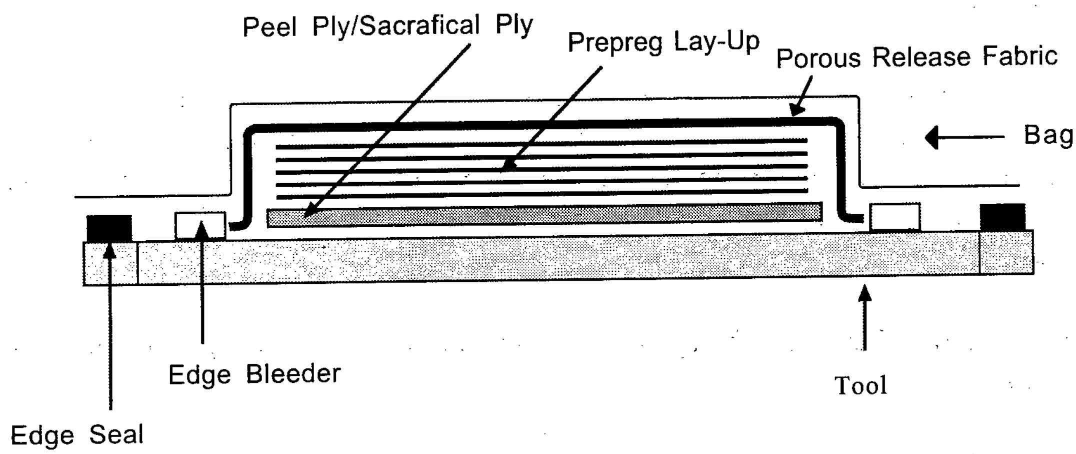


FIGURE 42. EDGE BLEED

6.7.2. Vertical Bleed.

Bleed outs are controlled to maintain predetermined thicknesses.

- The surface of the mold is prepared with the release agent.
- The sacrificial ply is laid up and is extended to anchor a flexible dam.
- The peel ply is carefully positioned and anchored so as to not interfere with anchoring the flexible dam.
- The composite plies are indexed, laid up, and rubbed out on top of the peel ply.
- The flexible dam is anchored to the sacrificial ply approximately 0.125 inch (3.2 mm) from the edge of the composite lay-up.
- The release fabric is laid up over the dam and the lay-up.
- A predetermined number of bleeder plies are laid up over the release fabric and extended only to the perimeter of the lay-up (sometimes they are stitched to the release fabric).
- A perforated Tedlar breather ply is laid up over the bleeders and extended to the flexible dam. The Tedlar contains 0.030-inch (7.5-mm) perforations 1 in. (0.254 cm) on centers.
- An edge bleeder is connected to the venting ports.

- Two layers of 181 style dry glass fabric are placed over the lay-up and extended to the edge bleeders.

- Caul plates or insulating layers are sometimes located over the composite lay-up. A 0.125 inch (3.18 mm) steel, aluminum, or transit plate provides adequate protection against sharp temperature increases. The intent is to maintain the same heating and cooling rates with the mold and to prevent local purging of resin during pressurization. Caul plates are also used to ensure a smooth, nonwavy surface.

- Two or more plies of dry fiberglass fabric are laid over the cauls to protect the bag against perforations.

- The sealer is applied around the perimeter of the edge bleeder.

- The bag is positioned and sealed.

- The bag contents are evacuated and smoothed, and the bag is checked and sealed against leaks.

- The bagged lay-up is ready to be cured.

In both edge and vertical bleed out systems, the amount of bleeder plies are calculated to reduce resin contents by predetermined amounts. The vertical bleed without caul plates is illustrated in figure 43.

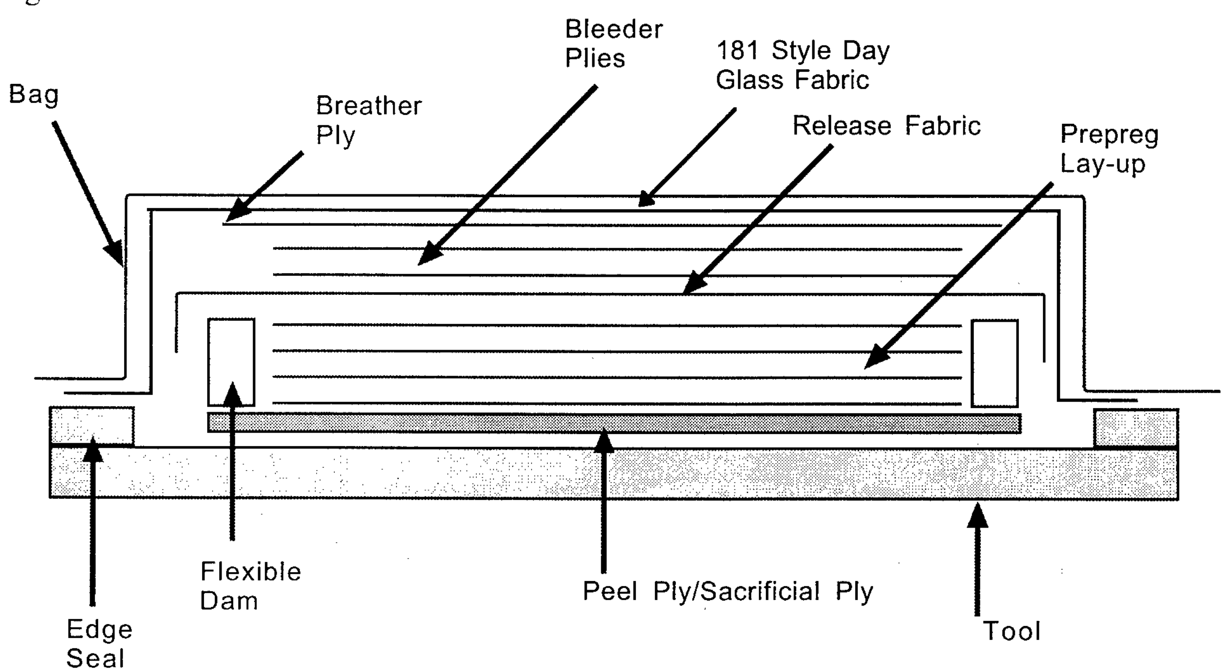


FIGURE 43. VERTICAL BLEED (WITHOUT CAUL PLATE)

Because of the high overall cost of composite parts and the requirement for pressure intensifiers, silicone-rubber vacuum bags which could be reused have been developed by government and industry. It was imperative to reduce the risk of losing production parts due to failure of nylon-film bags during curing. For temperatures up to 380°F (193°C) nylon film has been widely used once and discarded. Kapton polyimide film, sealed with silicone rubber, is applicable to temperatures in the 550°F (288°C) range; metal foils and mechanical clamping are used at higher temperatures.

6.8 NO BLEED PROCESS.

The curing of advanced composites without a bleeder system (no-bleed process) has been introduced to reduce cost and tooling complexity (see figure 44). Prepreg materials with a lower than normal resin content are used to increase the fiber volume fraction while maintaining ease of handling. For graphite/epoxy tape, the no-bleed prepreg has a nominal 35% resin content, compared to the 40% normally used. The plies are sealed off with a plastic film (Tedlar) or nonporous Teflon coated glass fabric. The entrapped air is removed from the laminate by diffusion through the plastic film or glass yarns connecting the lay-up and a perimeter bleeder system.

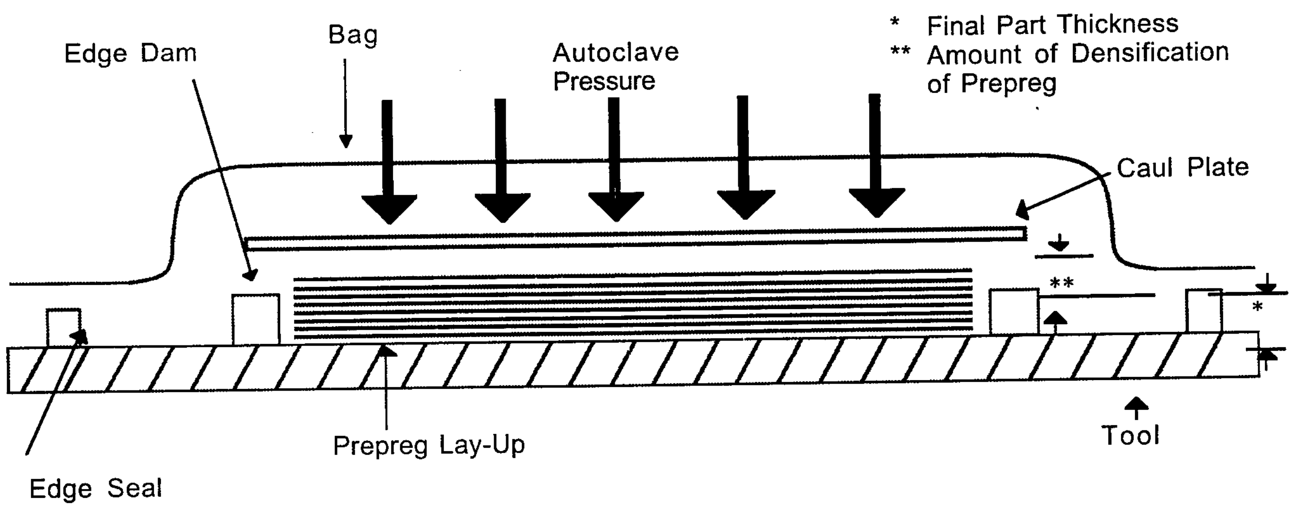


FIGURE 44. NO BLEED SCHEMATIC

7. MACHINING.

7.1 INTRODUCTION.

Machining techniques for high-modulus composites have been developed for use in the aerospace industry. However, some of the methodology is still being refined to reduce cost. Most of the current work is devoted to boron/epoxy, aramid (Kevlar)/epoxy, and graphite/epoxy. Each of these reinforcements have characteristics particular to themselves and, in turn, may impose unique machining requirements. In general, all of the conventional detail part operations (drilling, turning, and finishing) can be applied to the high-modulus composites, along with advanced technology processes such as water-jet cutting and ultrasonic machining.

Although composites often are molded to a near-net shape (that is, an almost finished shape), trimming, finishing, and assembly into larger structures may be required. Therefore, the trimming, finishing, and assembly of composite materials is an important consideration (see figure 45). In some of these processes, the potential for damaging or otherwise weakening the composite (delamination, fiber fraying, or drill breakthrough) is great and care must be taken to maintain the integrity of the composite.

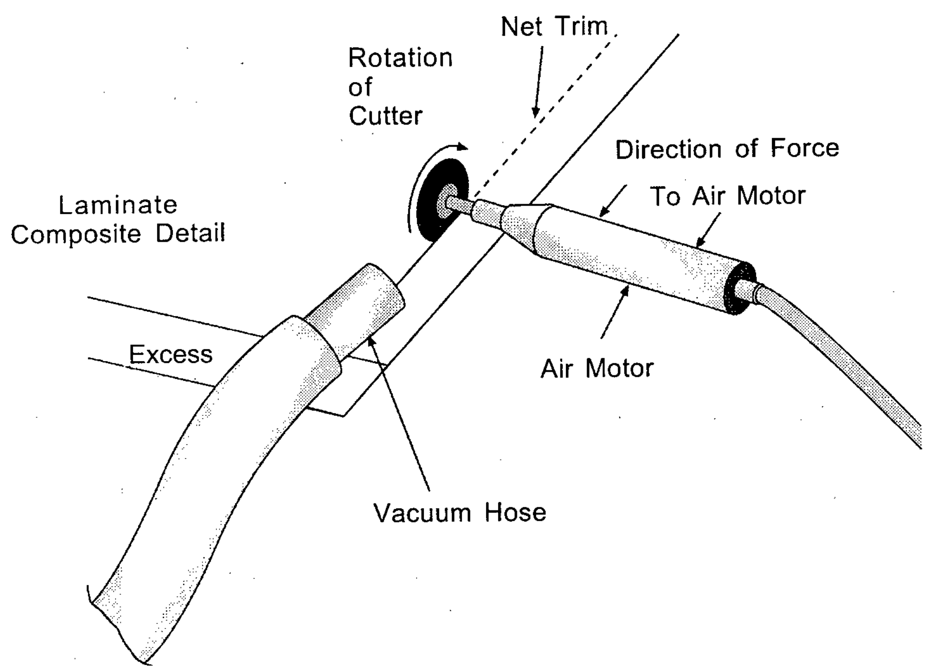


FIGURE 45. EDGE TRIMMING

The equipment and procedures used in cutting, drilling, and machining of composites differ from similar processes for either metals or plastics. The abrasive nature of the reinforcement requires process modifications, and the type of reinforcement (aramid, carbon or glass) also makes certain modifications necessary. Composite materials can be trimmed and cut more easily with

processes closer to grinding or abrasive cutting than conventional metal cutting which produces large chips. Cutting, drilling, and other machining processes are largely dictated by the type of reinforcement with minor modifications to allow for the degraded nature of the matrix. On the other hand, the processes of bonding and painting are largely dependent on the matrix material since these are chiefly surface phenomena.

7.2 TRIMMING AND MACHINING OF COMPOSITES.

Unique tools and techniques are required to trim and machine composite materials. The general goals of proper trimming and hole machining operations are:

- No splintering or delamination of surfaces that can be detected by visual examination.
- Surface finish of approximately 250 Ra.
- No discoloration due to overheating.
- Loose surface fibers, if any, originating from the hole boundary do not exceed 25 percent of the hole diameter in length. Loose fibers, if any, and splinters do not extend beyond the surface ply.

To meet these types of requirements specialized tooling is required to provide controlled feeds and speeds. For most applications the drilling of a hole in composite materials will require a two-step operation. The plain hole or the countersunk hole is drilled initially and then a reaming operation follows. When using a gun drill, a coolant is used to help flush chips from the hole. Commercial coolants that are specially formulated for these applications are available. When dry-drilling a hole, some type of vacuum system is required to contain the dust generated by the drilling operation.

Because matrices are used in most composites, some type of a backup on the drill exit side is always required when drilling to prevent material splintering on the exit side. Common materials used for backup are fiberboard, fiberglass laminate, wood, or aluminum. When edge trimming is done in a router fixture, the router fixture itself acts as the backup material.

Even when using the proper drills or cutters with a backup material, burns or splinters will often occur. The best method for removing these projections is with sandpaper. Generally, a grit of 320 or finer is used. A variety of models of hand power tools exist for drilling of composites.

7.2.1 Trimming Operations.

A host of processes are available for cutoff and/or trimming of high-modulus composites. The basic factors which enter into the process selection are straight versus curvilinear cutting, part size and configuration, rate and quantity requirements, and equipment availability or cost. In

addition to correct process selection, appropriate cutting tools must be utilized to achieve efficient fabrication. These cutting tools may range from conventional high-speed tool materials to the more exotic diamond-impregnated materials. The following will address both equipment and cutting tool considerations (see table 9). The trimming, drilling, grinding, and cutting of composites produces dust. These operations should be conducted in the proper environment and/or with the proper equipment (see figure 46).

TABLE 9. RECOMMENDED TOOL TYPES FOR THE CUTTING AND TRIMMING OF COMPOSITES

TRIMMING OPERATION	EQUIPMENT	CUTTER TYPE	SPEED	
			SURFACE FEET PER MINUTE	SURFACE METERS PER MINUTE
Straight Line Cuts	Radial Arm Saw Table Saw Drill Press Hand Router Disc Sander	Diamond Coated Circular Saw	2,000 to 12,000	610 to 3660
	Milling Machine (GR/EP&T1)	CARBIDE END MILLS T-302XX hss END MILLS T-302G6	60 TO 90	18 TO 27
Irregular Outline	Band Saw	Magniband Saw Blade	(portable) 1,000 to 2,000 (stationary) 2,000 to 12,000	(portable) 305 to 610 (stationary) 610 to 3660
	Pin Router or Hand Router	Diamond Router	1,000 to 6,500	305 to 1980
		Carbide Router Bit	1,000 to 6,000	305 to 1980
	Hand Router or Hand Drill Motor	Abrasive drum	1,000 to 6,000	305 to 1980
		Abrasive Disc-Flex Arbor (Mushroom)	400 to 2,400	122 to 732
Chamfer, Deburr	Hand	Abrasive Drum	N/A	N/A
Finish Operation	Hand	Abrasive Cloth	N/A	N/A

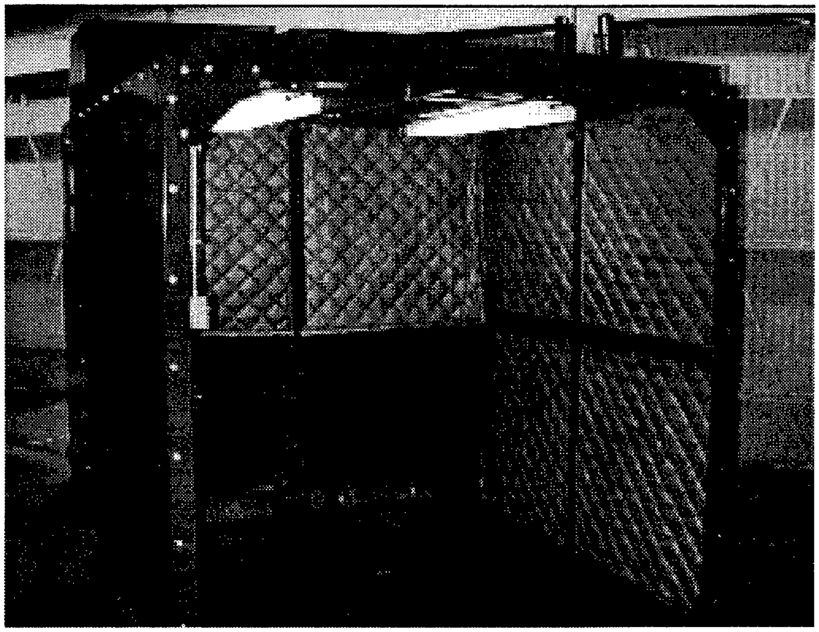


FIGURE 46. TRIMMING BOOTH

7.2.2 Trimming Kevlar.

The machining characteristics of composites reinforced with Kevlar are similar to those of wood. To obtain optimum results, shearing action using sharp blades with low heat generation is desirable. Particular attention should be given to the cutting of the outermost layer of the composite. Fibers in this outermost layer either must be restrained by external backing or the shearing action must be directed toward the interior of the composite. Adherence of resin to cutting surfaces is often the cause of apparent dulling of tools. Most trimming of Kevlar is done with a diamond wheel router combination. Grit edge tools are also widely used. These tools are tungsten carbide grit charged to wheel cutters, band saw blades, and saber saw blades. Trimming with these tools or blades will leave some edge fuzzing (loose fiber) but can be readily removed with light wet sanding. Note: sanding to be directed toward center of laminate.

7.2.3 Trimming Kevlar, Breakaway Method.

Net trim is accomplished with a fabricated trim fixture which is positioned over uncured laminate. Trimming is accomplished with a hook-blade knife using a pulling action along the edge of trim fixture. The trimmed excess or flash is retained in position on the mold after cutting. A nylon peel ply is laid up over the part and the flash to form a bridge.

Note: Trimming with conventional knife blades will damage tool surfaces, only a hook-blade knife is to be used on this operation.

The net trim, breakaway method of fabricating Kevlar laminates, is satisfactory for relatively simple contours and relatively simple edges. Thus, if a hook knife is used for trimming, a

thickness in excess of four plies then the interior radii should be avoided. The depth contour or draw of the part is limited by its complexity such that ply shifting will not occur during cure.

7.3 SAWING COMPOSITES.

Standard metal and woodworking equipment can be used for routine radial sawing and band sawing operations. Radial sawing provides a fast and accurate approach to composite cutting which can be achieved with either stationary or portable equipment. The single biggest drawback is its straight line cutting limitation.

Both graphite/epoxy and boron/epoxy laminates can be readily cut to a finished edge using 60-grit diamond-impregnated tools operating at 7000 rpm. However, diamond-impregnated tools will quickly clog if used on aramid (Kevlar)/epoxy. For this application, a hollow-ground, high-speed steel saw blade with 16 teeth/inch (6.3 teeth/cm) is very effective when run backwards. Band sawing offers the advantage of producing contoured cuts, but edge quality is generally poor and must receive a post-process finishing operation. The types of blades used for band sawing (graphite/epoxy, boron/epoxy, and aramid (Kevlar)/epoxy) are, respectively, medium grit carbide, 60-grit diamond plated, and HSS with a lapped raker set configuration. Operating speeds are generally 2000-5000 feet/minute (610-1525 m/minute) with the higher speeds used on aramid (Kevlar)/epoxy.

Cured laminates may be cut by band, circular, or saber saws. Clamping of the part is required to eliminate vibration which may cause delamination. The cutting edges should be checked frequently and their sharpness maintained.

- Skip Tooth Blade—4-6 teeth per inch. Primarily used for cutting nonferrous metals such as aluminum, magnesium, soft brass and bronze, in addition to plastics and nonmetallic materials. Skip Tooth Blades will generally delaminate thin fiberglass components. Thicker laminates allow a satisfactory cut; however, blades dull quickly because of the limited number of teeth on this type of blade.

- Fine-Tooth Blades—14-20 teeth per inch. Primarily used for cutting ferrous metals, thin sheet metal, and fiberglass material. Because of the greater amount of teeth per inch, abrasive materials such as composites have less effect in dulling this blade.

- Grit-Edge Blade—This blade has tungsten carbide particles fused to the cutting edge. Blades of this type will cut the largest variety of materials, from tool steel to ceramic material. Grit-edge blades come in two types: gulleted—for general cutting in materials 1/2 in. thick and greater and continuous—for cutting materials of thin cross section. Grit-edge blades will cut any composite combination with relative ease. Grit-edge blades can be reversed for cleaning or clearing. This cannot be done with conventional blades.

7.4 WATER-JET CUTTING.

The water-jet cutting process shows some potential for trimming high-modulus composites at pressures up to 60,000 psi (1.45 X 10^6 MPa). At this pressure, aramid (Kevlar)/epoxy can be cleanly trimmed while thin graphite/epoxy laminates may demonstrate minor delaminations (see figure 47).

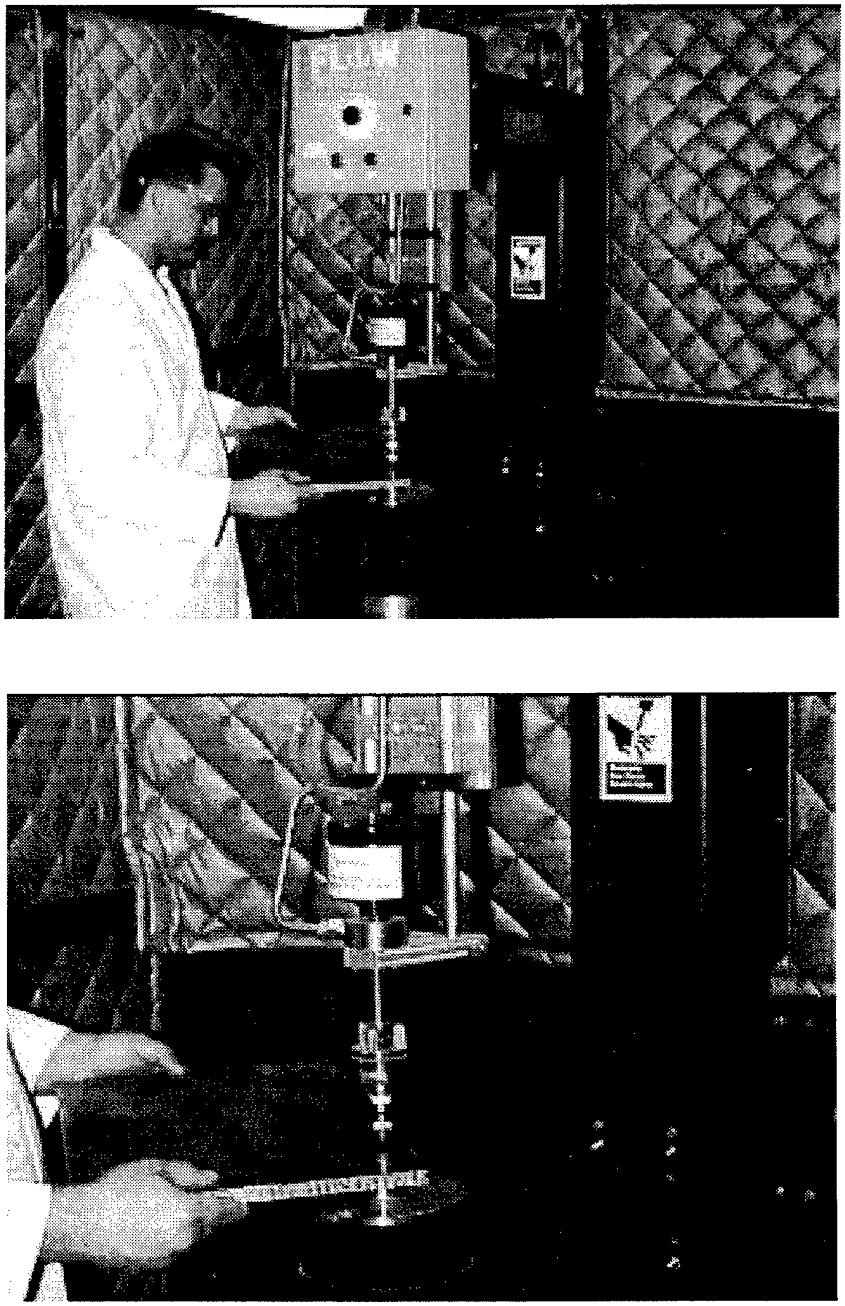


FIGURE 47. WATER-JET CUTTING A SANDWICH PANEL

7.5 ROUTING COMPOSITES.

Routing is an edge trimming operation which may be performed with manual or machine controlled equipment. The basic difference in routing of the various high-modulus composites is the type of cutting tool used. Diamond-cut carbides are effective for graphite/epoxy laminates. Diamond-coated (40- to 50-grit) router bits are required for the abrasive boron/epoxy and carbide opposed helix router bits are effective for aramid (Kevlar)/epoxy composites. Cutting speeds for these operations are generally obtained with 13,000- to 21,000-rpm routers.

Router speed should be at 20,000 to 35,000 rpm (30,000 rpm is preferred) in order to properly cut the Kevlar laminate. It is important to position the edge of the laminate at the exact junction of the two opposing helix angles of the router. Routers that appear to be dull are often filled with a fine film of epoxy resin on the cutting surface. This resin buildup can be removed with a suitable epoxy paint stripper such as R2134A.

7.6 GRINDING COMPOSITES.

Grinding and abrasive cutoff are effective methods for machining the high-modulus composites. Diamond wheels appear best, although silicon carbide and alumina wheels can be used. Coolants are required to prevent matrix thermal degradation, and speeds have been in the range of 3000-8000 feet/minute (915-2440 m/minute).

7.7 DRILLING COMPOSITES.

Drilling of graphite/epoxy can be accomplished with standard carbide drills (see table 10). Drills should be kept sharp to minimize breakout, and the use of particulate removal equipment is required since most operations are performed dry. As most laminated thermosets tend to shrink slightly after drilling, oversized cutting tools should be utilized to increase accuracy and maximize tool life. Drilling parallel to the lamination should be avoided since delamination often results. If parallel drilling is necessary, the drill point included angle should be increased and the workpiece completely clamped.

Drill fixtures should be employed whenever practical and should be designed to avoid breakout at bottoms and lifting at the top of the work. Generally, a drill speed of 400 ft/minute (122 m/minute) is adequate except for graphite/epoxy, where 900-1050 ft/ minute (275-320 m/minute) is desirable (see table 11).

Drilling of aramid (Kevlar)/epoxy requires that an alternate drill configuration must be used. One effective method is to use a Jancy type counterbore. This drill, operating at 300-400 sfm, can produce good quality holes (minimal fuzzing) even with HSS tool material. However, epoxy and fiber residue should be removed/cleaned from the drill after every five holes to maximize cutting ability.

TABLE 10. POINT TYPE INFORMATION FOR VARIOUS DRILL TYPES

DRILL TYPE	C-2 CARBIDE TIP	SOLID CARBIDE	COBALT H.S.S.
Jobbers Conventional	NAS 907 Point P-5	T302N7 Burr Point T302N12	NAS 907 Point P-5
Jobbers Core	-	MCTI Stds 14° to 16° clear	MCTI Stds 14° to 16° clear
Extension	-	-	-
Snake Conventional	T302N6	-	NAS 907 Point P-5
Snake Core	-	-	MCTI Stds 14° to 16° clear
Combination Drill/CSK	T302N5, and Spade T302N15	-	-
Flat Flute Drill	-	T302N8	-
Gun Drill (with a Stack Point)	T302XX	-	-

TABLE 11. TYPICAL DRILLING AND REAMING PARAMETERS

HOLE DIAMETER INCH MINIMUM, MAXIMUM	DRILLING		REAMING (IF REQUIRED) (3)	
	SPEED, RPM LAMINATES	FEED RATE, (1, 2) SEC/IN, (SEC/MM)	SPEED, RPM	FEED RATE, (1, 2) SEC/IN, (SEC/MM)
5/32 (3.97)	3000	15 to 30 (0.64 to 1.28)	3000	15 to 30 (0.64 to 1.28)
3/16 (4.76)	3000	15 to 30 (0.64 to 1.28)	3000	15 to 30 (0.64 to 1.28)
1/4 (6.35)	3000	15 to 30 (0.64 to 1.28)	3000	15 to 30 (0.64 to 1.28)
5/16 (7.94)	1800	15 to 30 (0.64 to 1.28)	1800	15 to 30 (0.64 to 1.28)
3/8 (9.53)	1000	15 to 30 (0.64 to 1.28)	1000	15 to 30 (0.64 to 1.28)

Boron-reinforced laminates require diamond-impregnated tools due to the abrasive characteristics. Diamond tools are utilized in a metal matrix but are sensitive to heat and thus require a forced water coolant. Typical speeds are 3,000-5,000 rpm at a 1-inch/minute (2.54-cm/minute) feed. Thick lay-ups require ultrasound attenuation to speed up the process and reduce wear on cutting bits.

Specialized cutting equipment is required when working with graphite composites that have layers of metallic materials such as aluminum or titanium which is interspersed among the nonmetallic layers, as is quite common in hybrid aircraft structures. For such interlayered laminates, care must be taken not to damage composites with metal chips.

7.8 MACHINING COMPOSITES.

Specialty machining, such as automatic screw machining, gear cutting, shaving, reaming, blanking, and piercing, have been successfully conducted with laminated thermosets. Because these processes vary with the specific type of equipment used, standardized techniques are not applicable.

Conventional metalworking mills, lathes, circular saws, router cutters, and various abrasive materials have been used with only minor modifications to trim, cut, and shape cured composite materials. Power feed drills that control feed rate and turning speed are recommended due to improved hole quality. In most cases, the cutting speed (spindle speed) should be increased and the feed rate decreased relative to normal values used for metal machining. Optimum feeds and speeds can vary significantly depending on the resin/fiber system and on the thickness of the materials. Typical values for cutting (machining) many thermoset composites are 600 to 1,000 ft/min (180 to 300 mm/min).

7.9 TRIMMING AND FINISHING TOOLS.

The air motor is probably the most widely used tool in the aircraft industry. It comes in two sizes 2,500 and 4,400 rpm. This tool is primarily used for drilling; however, it can be used with a disc sander, hole saws, or counterbores. It is air operated and trigger controlled. The speed of this tool can be controlled with an air regulator. Chuck range is 0 to 1/4 inch.

Disc holder is another widely used tool used in combination with an air motor. It has a 1/4-inch shank and a rubber pad. Sanding discs that are used are self adhering and come in 36, 60, 80, 20, and 240 grit. Disc holders come in 3, 2, 1 1/2, 1, and 1/2 inch diameters.

Hole saws are used with an air motor to cut holes in thin composite materials. They come in many sizes.

The air router is used for trimming composites. It has a lever type trigger and operates at 30,000 rpm. The air exhaust is at the cutting end. The chuck will accept any cutter with a 1/4-inch shank. This tool is very delicate and should never be dropped.

Diamond wheels are used to trim composites. Diamond dust is fused to the cutter wheel. This cutter is meant to be operated at a high speed in an air router. If the wheel becomes clogged it can be readily cleaned by soaking it in MEK. Diamond wheels come in two sizes, 1 and 2 inch

diameters. Note: Diamond wheels are very expensive and should not be dropped. A wheel bent from careless handling will vibrate at high speeds, resulting in delamination during trimming.

A rotary file is used in air routers for trimming and cleanup work. Rotary files are made of high carbon steel and carbide. Because of the abrasive quality of fiberglass, carbide is used. Carbide is very brittle so use with care.

7.10 FINISHING AND POLISHING.

Laminates are finished by sand blasting, honing, lapping, buffing, and polishing. Sand blasting employs both sand and alumina abrasives with a wide range of grit size (980240 grit) and a range of air pressure. Sand blasting is used either to obtain a desired nongloss finish or as a step in an assembly process. Honing can be conducted dry or wet, and several types of honing machines are available. Coarse and fine grit alumina abrasives are used in water and oil vehicles; the technique utilized is a direct function of the specific honing machine. Laminates have been honed to a 30-microinch (7600-micrometer) finish without difficulty. Finer finishes are possible for laminates by lapping either by hand or on machines. Buffing and polishing are generally the finishing methods for obtaining a mirror-smooth surface. The buffing wheel consists of muslin discs, and the polish is a greaseless composition of silica powder. The wheel is operated at slow speeds with light workpiece pressures.

7.11 MACHINING OF THERMOPLASTICS.

Although the machining of unreinforced thermoplastics is a well known art, it is complicated by the wide property differences among a large number of available materials and reinforced thermoplastics (fiberglass, aramid (Kevlar), and graphite). The generalized machining suggestions given are for the large majority of thermoplastics, although anomalies do exist.

All thermoplastic materials can be shaped and finished with common equipment used for machining metals. In addition, many tools specifically used for woodworking, such as routers, shapers, and sanders, are well suited for thermoplastic materials. Since many materials are available in the form of sheets, blocks, slabs, rods, tubes, and other cast and extruded shapes, initial prototypes are frequently made entirely by machining.

The main problems encountered when machining thermoplastic materials are due to the heat built up by friction. As the resin and cutting tools begin to heat up, the plastic can distort or melt. This can produce a poor surface finish, tearing, localized melting, welding together of stacked parts, and jamming of cutters.

It is important to prevent the part and cutting tool from heating up to the point where significant softening or melting takes place. Some plastic materials machine much easier and faster than others due to their physical and mechanical properties. Generally, a high melting point, inherent lubricity, and good hardness and rigidity are factors which improve machinability. The following list provides information which can help prevent overheating of the part and cutting tool.

- Coolants should be used.
- Machinery should be operated at high speeds.
- There should be liberal clearances on cutting tools.
- Light cuts and slow feed of the workpiece should be used. Turning tools should be ground to provide rake angles that minimize tool cutting and thrust forces.
- Slow spiral drills designed for thermoplastics should be used.
- Tools should be carbide-tipped or utilize the special high-speed steel tools designed for plastics.
- The workpiece must be properly supported to avoid distortion under cutting pressures.
- Allowances for plastic memory and shop room temperature should be made to insure accurate machining.
- Tool bits and cutters should be sharp, since dull tools increase forces on the workpiece.

8. QUALITY ASSURANCE.

Federal Aviation regulations require that adequate inspection and quality assurance procedures be employed in the manufacture and maintenance of composite civil aircraft structures. Once composite structures are put into service, it is the operator's responsibility to ensure continued structural integrity of the various components. To aid the operator in maintaining his aircraft, a maintenance manual is created to provide, where appropriate, inspection, maintenance, and repair procedures, along with acceptance/repair/rejection criteria for composite structures.

This section of the handbook is devoted to a description of components of the quality control plan for a composite aircraft structure and to a discussion of the inspection and quality assurance techniques that are useful in the detection and quantification of the various defects in composite structures. The defects themselves are divided into three categories: (1) defects in the prepreg materials, (2) manufacturing-related flaws, and (3) service-related flaws.

Quality control in a production environment involves inspection and testing of composites in all stages of prepreg manufacture and part fabrication. Tests must be performed by the material supplier on the fiber and resin as separate materials, as well as on the composite prepreg material. The user of the prepreg must perform receiving inspection and revalidation tests, in-progress control test, and nondestructive or, in some specialized cases, destructive inspection tests on finished parts. These types of inspections are described in the following sections and normal industry practice is discussed.

The quality assurance of a composite structure (parts) requires a nondestructive inspection (NDI) procedures. The first step in the NDI procedures is the detection of the presence of defects and the measurement of the extent of damage. This is accomplished using an appropriate NDI method during the manufacturing and service stages of the structural component. The second is the determination of the acceptability of the recorded defects. This is normally accomplished by comparing the measured defect sizes with established acceptance-repair-rejection criteria. These are established by the manufacturer and are a function of type of defect, its location, and the strength criticality of the part.

8.1 QUALITY CONTROL.

Structural composite fabrication is not one simple operation but a complex sequence of operations. The success of each step depends on everything that has been done up to that point. At every step in the process, both the operator and the inspector must exercise the highest degree of control in strict accordance with the process specification for each individual job.

The entire composite or bonding process must be carefully controlled in order to ensure the reliability of the end product. Material specifications provide means of assuming material quality. Engineering specifications lay down the ground rules for structural composite

fabrication; manufacturing directives give the how-to rules for techniques and procedures; the Quality Control inspectors make sure the specifications and standards are followed.

During the manufacturing stage of a composite structure, the individual components are independently available for careful inspection and review. Consequently, a large volume of high-quality NDI records are obtained in comparison to the records obtained for the assembled structure. An inspector generally finds it difficult to locate and measure the size of all the significant flaws in an assembled structure using NDI tools that were developed for the individual components. Therefore, except for hole and bolt inspections, assembled structures are rarely inspected.

8.2 MATERIAL QUALITY ASSURANCE.

Composite materials are inherently more variable than single-phase, one-component materials such as metals, metal alloys, plastics, or ceramics. Therefore, the testing results for composites, although using a similar test or procedure, will be more scattered and difficult to interpret than single component materials. This variability is most often treated statistically. A fundamental knowledge of statistics (normal distribution, standard deviation, variance, and probability) is helpful. A good guidance to statistical methods can be obtained from MIL-HDBK-17.

Testing for composites follow standard testing procedures as defined by standards of The American Society for Testing and Materials (ASTM). These include tests on fibers, neat resin, prepregs, and laminates.

8.2.1 Receiving Inspection.

The composite material user typically prepares material specifications which define incoming material inspection procedures and supplier controls that ensure the materials used in composite construction will meet the engineering requirements. These specifications are based on material allowables generated by allowables development programs. The acceptance criteria for mechanical tests must be specified to assure that production parts will be fabricated with materials which have equivalent properties as the materials used to develop the allowables.

The user material specifications typically require the suppliers to provide evidence that each production lot of material in each shipment meets the material specification requirements. This evidence will include test data, certification, affidavits, etc., depending upon the user quality assurance plan and purchase contract requirements for a particular material. The test reports contain data to verify the conformance of material properties to user specifications and acceptance standards.

Acceptance test requirements may vary from user to user. However, the tests must be sufficient to assure the material will meet or exceed the engineering requirements. A typical example of

receiving inspections consist of tests or affidavits of the material quality of the individual components of composite, matrix and fiber, prepregs, and cured laminate.

Receiving inspection test requirements should address test frequency and, in the event of initial failure to satisfy these requirements, retest criteria. Test frequency is a function of the quantity of material (weight and rolls) in a batch. Typical testing may include specimens from first, last, and random rolls. A retest criteria should be included for the cured lamina test so that the material is not rejected because of testing anomalies. If a material fails a test, a new panel from the suspect roll of material should be fabricated and used to rerun that specific test. If a batch has multiple rolls, that test should run on material from the roll before and after the suspect roll in order to isolate the potential problem. If the material fails the retest, the entire batch should be reviewed by material engineering. As use and confidence increase, the receiving inspection procedure can be modified. For example, the test frequency can be decreased or certain tests can be phased out.

8.2.2 Fibers and Matrices.

The testing of single fibers is principally of interest to the material suppliers and is not generally used by the aircraft manufacturer. Fiber manufacturers are interested in maintaining the uniformity of fiber performance; therefore they test fibers as part of their quality control procedures. Fiber manufacturers test fibers as part of their ongoing research into the development of new or improved fibers. Tows, strands, or fabrics are more commonly tested when properties of bare fibers, without the matrix, are determined.

The principal physical tests on fibers are density, diameter, and fiber visual characterizations. The density can be expressed in normal weight per volume terms (such as g/cc) but for fibers, it is also commonly expressed as a denier. A denier is the weight in grams for 9000 meters of fiber. It is, in a way, a linear density. The lower the denier, the finer the fiber. Yarn deniers for Kevlar typically range from 55 to 2130. Filament diameter can be measured directly by microscope or some similar technique or calculated if the denier and density are known.

The visual detection of fiber fraying or twisting is often some of the most important tests. These defects may interfere with the proper coating of the fibers with a resin, especially in a prepreg where the fibers must be collimated and the resin content controlled carefully.

The properties of both uncured and cured resins are important in determining the behavior of the resins. In uncured resins, the resin manufacturers are concerned about the formulation while the composite manufacturers are concerned about the cure characteristics (for thermosets) or the melting characteristics (for thermoplastics).

The volatiles content of the thermoset resin may also be important in determining the tack, drape, and handling characteristics of the prepreg. The volatiles content most often is determined by weight loss upon heating.

If thermoset resins are to be cured, then the completeness of that cure is of obvious interest. A test usually used to measure this completeness is called differential scanning calorimetry (DSC).

Several composite materials must show chemical resistance to a variety of solvents, including fuels, lubricants, hydraulic fluids, paint strippers, and water. In general, the thermoset materials are better in this resistance than are the thermoplastics, although high crystallinity improves the performance of the thermoplastic.

8.2.3 Prepregs.

Structural laminates are generally fabricated using prepregs, and the quality of the laminate is very dependent on the quality of the prepreg. The prepreg quality is affected by the quality of the fibers and matrix used to form the prepreg. This subsection describes the procedures that are currently followed in the aircraft industry to ensure adequate quality of the prepreg material. The described procedures are divided into three categories addressing the physical, chemical, and mechanical properties of the prepreg.

The exact compositions of most prepregs are proprietary. Prepreggers certify physical and processing properties and the compliance to the composite property standards delineated in company procurement specifications. Military and industry specifications establish general standards for quality controls of prepregs. Company procurement and processing specifications amend the standards to suit specific applications or particular constructions. Standards for the quality controls of composites and processing characteristics include the following.

Composites:

- Resin or reinforcement content measured by solvent extraction, pyrolysis, or chemical digestion methods.

- Volatile content measured by partial pyrolysis at standard test conditions.

Processing characteristics:

- Tack, a measure of adhesion qualities.

- Flow, a measure of resin that can be squeezed from a standard specimen as it cures between press platens at standard temperatures and pressures.

- Gel time, a measure of the time a standard specimen remains between heated platens before the resin no longer adheres to a probe.

8.2.4 Cured Laminates.

To verify certified prepreg data, suppliers recommended cures for quality control test panels are required. Tensile strengths, compression strengths, flexural strengths, and interlaminar and in-plane shear strengths relative to the principal directions of the cured prepreg are usually tested to prove compliance to the material specification.

8.3 PROCESS VERIFICATION.

The quality assurance department for the user generally has the responsibility for verifying that the fabrication processes are carried out according to engineering process specification requirements. This encompasses a wide range of activities (described below) to control the fabrication process.

8.3.1 Material Control.

The user process specifications must set the material control for the following items as a minimum.

- Materials are properly identified by name and specification.
- Materials are stored and packaged to preclude damage and contamination.
- Perishable materials, prepregs, and adhesives are within the allowable storage life at the time of release from storage and the allowed work life at time of cure.
- Prepackaged kits are properly identified and inspected.
- Acceptance and reverification tests are identified.

8.3.2 Materials Storage and Handling.

The user material and process specifications set procedures and requirements for storage of prepregs, resin systems, and adhesives to maintain acceptable material quality. Storing these materials at low temperatures, usually 0°F or below, retards the reaction of the resin materials and extends their useful life. Negotiations between the supplier and user result in an agreement on how long the supplier will guarantee the use of these perishable materials when stored under these conditions. This agreed to time is incorporated as one of the requirements in the user material specification.

8.3.3 Material Storage.

Materials are generally stored in sealed plastic bags or containers to prevent moisture from condensing on the cold material and migrating into the polymer when it is removed from the freezer and allowed to warm up to ambient temperature. The time interval between material removal from the freezer and when the material bag or container may be opened is generally empirically determined. Physical characteristics such as material roll, stacking height thickness, or material type (e.g., tape vs. broad goods) are considered when determining this time interval. Therefore, the user should have procedures that prevent premature removal of materials from storage bags or containers before material temperature stabilization occurs.

8.3.4 Tooling.

The tooling (molds) to be used for lay-up are subject to tool proofing/qualification procedures. This demonstrates that the tooling is capable of producing parts that conform to drawing and specification requirements when used with the specified materials, lay-up and bagging methods, and cure profile. Also, cured material specimens made from the tool should be tested to ensure they meet specified mechanical and physical properties. Tool surfaces must be inspected before each use to ensure the tool surface is clean and free of conditions which could contaminate or damage a part.

8.3.5 Facilities and Equipment.

The user will establish requirements to control the composite work area environment. These requirements are a part of the user's process specifications. The requirements should be commensurate with the susceptibility of materials to contamination by the shop environment. Inspection and calibration requirements for autoclaves and ovens must be defined.

Contamination restrictions in environmentally controlled areas typically prohibit the use of uncontrolled sprays (e.g., silicon contamination), exposure to dust, handling contamination, fumes, oily vapors, and the presence of other particulate or chemical matter which may affect the manufacturing process. Conditions under which operators may handle materials should also be defined. Lay-up and clean-room air filtrations and pressurization systems should be capable of providing a slight positive overpressure. Some typical restrictions are listed below:

- Only authorized personnel are to be allowed in this area.
- No smoking or eating in this area.
- No drilling or sanding or dust producing work in this area.
- No hand creams or hand cleaners are to be used in this room.

- Graphite pencils or ink pens are not to be used on any bond surfaces. Grease pencils are not to be used under any condition.

- No silicones are to be used in this room other than silicone bags and fillets.

- Keeping your work station or area clean, neat, and orderly.

- Anyone working in bonding area while handling adhesives or prepregs WILL wear approved gloves.

- No tools, molds, or detail parts permitted unless they are clean and free from contamination of dust or oil and/or grease.

- No tools or molds are to be coated with mold release or cleaned in this area.

- Overhead type entrance doors are to be used only for moving tools to autoclave because of air conditioning and humidity control requirements. These doors are not for personal access.

- All materials used in this area will comply to storage and out time requirements.

8.3.6 In-Process Control.

During lay-up of composite parts, certain critical steps or operations must be closely controlled. Requirements and limits for these critical items are stated in the user process specifications. Some of the steps and operations to be controlled are listed below:

- Verification that the release agent has been applied and cured on a clean tool surface.

- Verification that perishable materials incorporated into the part comply with the applicable material specifications.

- Inspection of prepreg lay-ups to assure engineering drawing requirements for number of plies and orientation are met.

- Inspection of honeycomb core installation, if applicable, and verification that position meets the engineering drawing requirements.

- The user paperwork should contain the following information.

    - Material supplier, date of manufacture, batch number, roll number, and total accumulated hours of working life.

- Autoclave or oven pressure, part temperatures, and times.
- Autoclave or oven load number.
- Part and serial number.

8.3.7 Part Cure.

Requirements must be defined in user process specifications for the operating parameters for autoclaves and ovens used for curing parts. These include heat rise rates, times at temperature, cool-down rates, temperature and pressure tolerance, and temperature uniformity surveys in the autoclave or ovens.

8.3.8 Process Control Specimens.

Many manufacturers require special test panels to be laid up and cured along with production parts. After cure, these panels are tested for physical and mechanical properties to verify the parts they represent meet the engineering properties.

The requirements for physical and mechanical testing are frequently defined by drawing notes which designate a type or class for each part. Noncritical or secondary structure may require no test specimens and no testing. Critical or safety-of-flight parts may require complete physical and mechanical testing.

During early composite material production, most users required test for 0° flexure strength and modulus and short beam shear strength. However, in recent years these tests have been changed by many manufacturers to require glass transition temperature, per ply thickness, fiber volume, void content, and ply count on samples taken from designated areas on the production part.

8.4 PART INSPECTION.

Having assured in-process control, the detail composite parts must also be inspected for conformance to dimensional and workmanship requirements and nondestructively inspected for processing-induced defects and damage. In practice, all flight critical parts are 100% inspected by NDI. Nondestructive tests are supplemented by destructive tests whenever assurance cannot be gained by nondestructive techniques alone. These tests include periodic dissection of the part to examine the interior of complex parts and mechanical testing of coupons.

8.4.1 Damage Awareness.

Composite materials have complex failure modes that may have developed from delaminations, fiber disbonds and breakage, and matrix microcracks. Therefore, it is important that these defects be detected before final part failure, which is usually accomplished by fiber rupture.

Effective damage assessment is a vital link in determining the proper composite repair method. Steps in assessing damage are as follows:

- Location of damage

- NDI evaluation of damage area to determine type, depth, and size. Note: Refer to nondestructive testing manual for selection of inspection equipment, procedures, and other information. Adjustments to standards may be required for specific damage assessment.

- Reassessment after damage removal. Note: (a) NDI methods may not detect defects beyond the first layer of damage. (b) Damage (delamination) tends to propagate during material removal.

Composites are susceptible to many defects and damages that are introduced during the prepreg fabrication, laminate manufacturing, structural assembly operations, and during the service life of the structural part. The critical defects and damages are subsequently identified, and the concept of zoning a structure at the design stage, based on damage susceptibility, is introduced.

8.4.2 Defects and Damages in Composites.

The potential defects and damages in composites, from the uncured prepregs to structural laminates in service, may be grouped into three categories: (1) prepreg defects and damages, (2) manufacturing-related defects and damages, and (3) service-induced damages. Each of these categories is discussed.

8.4.3 Prepreg Defects and Damages.

Defects and damages may be introduced into prepregs either during the preimpregnation process or as a result of handling and storage-related problems. Defects introduced during the preimpregnation process are generally detected at the incoming material inspection stage. If any of these are unacceptable, the material is rejected and not used for the fabrication of structural parts. Storage and handling-related problems can also introduce damage in the prepreg material and should be minimized by establishing rigid handling specifications.

An often overlooked area for potential composite damage is material handling prior to processing. As emphasized in section 1, traceability of preimpregnated materials is very important. The damage to the prepreg may or may not be visable. The damage is more subtle and takes place at the chemical level and only appears after the prepreg has been processed. As the prepreg sits out at ambient temperature it begins to age. That's to say the material begins to crosslink. As this begins to take place the prepreg can begin to get stiff and boardy. When processed, the prepreg may not flow as well with this crosslinking and could cause porosity in the part or a failure if the plies fail to bond to each other.

A method for checking this and to assure the prepreg was processed properly is to include a test coupon within the bag for the part. The test coupon can be a separate panel under the same bag or under a bag that is connected to the bag the part is cured under. Another method is to lay-up the part with enough excess that the test coupon can be cut from the excess. Either way you now have a coupon that can be used for destructive testing and will tell you if the part was processed properly and if the prepreg was within established tolerances.

Most of these defects and damages may be visually detected or measured, and some of them may be suspected to be present when storage requirements are violated. Unacceptable defective or damaged prepreg will be rejected because their presence affects the quality of the fabricated laminate.

8.4.4 Manufacturing-Related Defects and Damages.

A structural laminated part is initially fabricated using any of the processes and is subsequently machined, if necessary, and joined to other parts to assemble the overall structure. Critical defects and damages that are potentially introduced during these manufacturing operations include porosity and delaminations (process-related), surface flaws (handling-related/assembly-related), flawed fastener holes (bolted structures), and poor bonding quality (bonded structures).

Joining of composites is done with adhesives and this has led to several design capabilities not often used with metals. Traditional metal fastening techniques can also be used but care should be taken to prevent pull-through failures either by the head or tail and corrosion between the fastener and the composite. A brief description of these defects and damages is presented in table 12.

TABLE 12. DAMAGE DEFINITIONS

DAMAGE TYPE	ONE FACTOR IN DETERMINING SEVERITY
Delamination	Separation of adjacent composite plies
Crack	Fractures in matrix and/or fibers
Abrasion	The wearing away of a portion of the surface by either natural (e.g., rain), mechanical (misfit), or man-made (e.g., oversanding) means, and penetrates only the surface finish
Dent	A concave depression that does not rupture plies or debond the composite structure
Gouge	A special type of dent where some, but not all, composite plies are severed
Scratch	An elongated surface discontinuity due to damage that is very small in width compared to length
Impact damage	Damage from contact with a foreign object
Cut	Fibers severed by a sharp edge

8.4.4.1 Porosity.

In determining porosity, the specimens are first weighed in air and water, then the resin material is subsequently dissolved in an acid solution. Certain specifics of the fiber reinforcement and the resin material are assumed and void volume percentages are computed in accordance with ASTM standards such as D3529. Void volume computation based on chemical analysis measurements is very dependent on accurate fiber and resin density values. Porosity quantification using an image analysis system interrogates a specific cross section in the porous laminate, and an average of measurements at many locations is required.

8.4.4.2 Delaminations.

Delaminations are separations between adjacent plies in a laminate or between structural laminates such as skin and stiffener that are cocured (see figure 48). At the fabrication stage of laminates, delaminations may be introduced because of (1) a failure to remove the prepreg peel ply (or backing paper) during the lay-up operation, (2) an inclusion of nonadhering foreign objects during lay-up, and (3) an inadvertent use of moist prepreg. Delaminations are easily detected for flat areas using an ultrasonic inspection technique. For curved parts and corners, X-ray is more reliable.

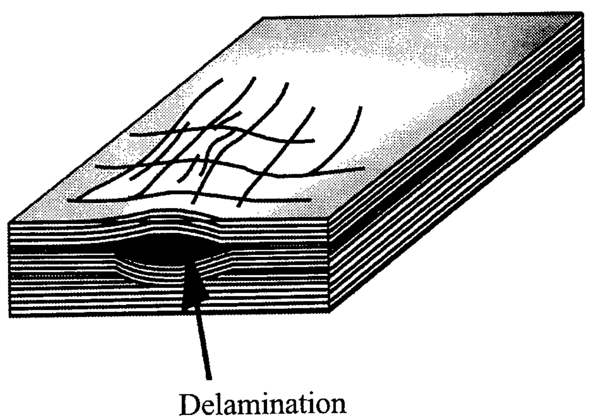


FIGURE 48. DELAMINATION

8.4.4.3 Surface Flaws.

Fabricated laminates are prone to many surface flaws that may be introduced during assembly-related handling operations or during service. These flaws include surface scratches, gouging, indentations made by the dropping of tools, and some laminate flaws are due to fluid spills (see figure 49).

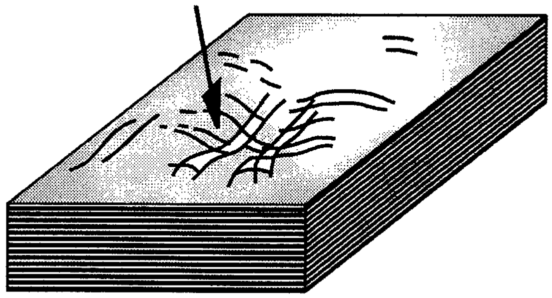


FIGURE 49. SURFACE DEPRESSION

Surface flaws are easily detected visually, and their sizes can be measured accurately. However, at gouged locations or impact-damaged locations, an ultrasonic inspection is also recommended to detect and measure the size of internal damage.

8.4.4.4 Flawed Fastener Holes.

In structural laminates that are mechanically fastened to other parts, holes must be drilled in accordance with established specifications. Nevertheless, the presence of flaws at fastener hole locations are commonplace. These flaws include cratering the hole surface, broken and separated fibers at the drill exit side of the hole, delaminations near the exit surface, and a slight tilt (<10 degrees) in the axis of the hole from the normal to the laminate surface.

8.4.5 Production and Service.

The following is a list of flaws experienced in production of composite structures

- External delamination, loose fibers, disbonding
- Internal delamination, blister
- Oversized hole
- Broken fibers at exit side of hole, breakout
- Tear-out or pull-through in countersinks
- Prepreg variability exceeding preset levels
- Resin-starved surfaces
- Resin-rich or fiber-starved areas
- Excessive porosity, voids
- Scratch, fiber breakage, damage done in handling
- Dent, no fiber breakage, damage done in handling
- Fiber breakaway from impact surface
- Edge delamination, splintering
- Overtorqued fastener

- Split tow, fiber separation
- Edge notch or crack
- Corner notch or crack
- Mislocated hole—not repaired
- Mislocated hole—resin refilled, redrilled
- Marcelled fibers
- Wrinkles, waviness, miscollimation
- Reworked areas
- Missing ply or plies
- Foreign particle, contamination, inclusion
- Out-of-round hole
- Wrong material
- Misoriented ply
- Ply overlap
- Ply underlap, gap
- First-ply separation
- Improper fastener seating
- Variable cure, poor spatial temperature in oven
- Figure 8 hole
- Nonuniform bond joint thickness
- Off-axis drilled hole (i.e., not perpendicular to surface)
- Countersink on wrong side of laminate
- Mislocated cocured assemblies in same tool
- Tool impressions
- Burned drilled holes from high-speed drilling
- Pill and fuzz balls
- Undersized fasteners
- Dent, hidden fiber breakage from production and mishandling
- Grossly nonuniform agglomerations of hardener agents
- Misfitting parts cutting fibers in fillet, poor seating design
- Overwarpage of parts from poor tooling
- Process control coupon thickness not constant or misrepresentative

Service incurred defects are listed below:

- Impact damage (matrix cracking, delaminations, fiber breakage)
- Delamination of plies
- Disbonds (between parts such as stiffeners and skin or honeycomb and skin)
- Cracks
- Hole damage

- Water entrapped in honeycomb
- Lightning strike damage
- Burn/overheating

8.5 NONDESTRUCTIVE TESTING.

The purpose of nondestructive testing (NDT) is to identify and measure abnormal conditions, especially defects, and to do so without degrading or impairing the utility of the sample in any way.

The NDT methods are the principal means of detecting damage to composite parts. These methods which include visual inspection, using a tap hammer, ultrasonics, acousto-ultrasonic, acoustic emission, radiography, holography, and thermography give information about delaminations, cracks and other damage types. However, the NDT methods are limited in assessing the extent of the damage or the possible causes. Without additional tests, an evaluation on the in-use performance of a damaged part is not generally possible. In an effort to bring some order to NDT damage assessment, several types of damage have been defined. Although not quantitative, these definitions are useful, especially in field situations for deciding the amount of repair that must be done to correct the damage. They are also useful in assessing possible causes of the damage.

8.5.1 Limitations of NDT.

One of the major dangers encountered in presenting data on nondestructive testing techniques is that the reader may be given the false impression that a technique is a panacea for all problem solutions. Each of the techniques that will be discussed has application to certain requirements, but no one technique universally obviates the need for any of the others.

The most efficient testing system may include all known nondestructive techniques; however, until appropriate techniques for all applications have been developed, no system of evaluation can be completely efficient.

8.5.2 Visual Inspection.

Visual inspection is inexpensive and relatively easy. However, if the inspected material is not transparent, like composites, it is only capable of finding flaws that are evident on the visible surface. Internal flaws in composites, such as delaminations, disbonds, and matrix crazing are not detectable. In addition, tight surface cracks and edge delaminations may not be detectable. Visual aids such as mirrors, borescopes, and magnifiers are portable and may be used to facilitate detection. Visual inspection results may be recorded in the form of photographs, if desired. The surface to be inspected should be clean and free of conditions that may mask or obscure defects.

Careful visual examination is the most convenient and widely used NDT inspection method. A schematic of such an inspection with an aid of incident light beam is shown in figure 50. Defects that may be observed include discoloration (possibly due to overheating), foreign matter, cracks, scratches, dents, blisters, porosity, resin-rich and resin-starved areas, wrinkles, and to some extent, voids and delaminations. Aids to the eye such as intense light and a magnifying glass can be helpful. Reflected light is used for observing surface irregularities and other defects while transmitted light helps reveal defects within the specimen.

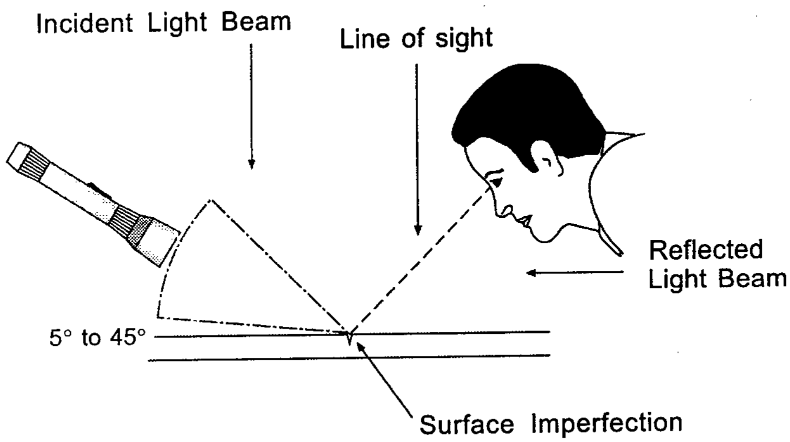


FIGURE 50. VISUAL INSPECTION

Visual inspection can be enhanced by using surface impact detection methods. For example, some composite parts can be coated with a clear or white paint containing microcapsules with colored pigment. When the surface is impacted, the microcapsules burst and the pigment becomes visible. Another method uses a thin foam layer covered with S2 glass which shows the damage visually much more easily than a carbon/epoxy surface.

8.5.3 Low-Frequency Bond Testers.

8.5.3.1 Theory of Operation.

The term, low frequency refers to bond testers which operate below 100 kHz and are generally called sonic bond testers. They generally do not require the use of a liquid couplant (dry coupled) and operate in the audio or near audio frequency range.

Resonance-impedance instruments may operate in either the sonic or ultrasonic frequency range and generally require the use of a liquid couplant (wet coupled). Different techniques of transmitting and receiving energy have been developed for low-frequency bond test applications. Each technique introduces a pressure wave into the specimen and then detects the transmitted or reflected wave. The following sonic, or acoustic mechanical principles are used to evaluate the damping characteristics of the specimen.

8.5.3.2 Pitch/Catch Impulse Test Method.

This method uses a dual-element, point contact, noncouplant, low-frequency sonic probe. One element transmits acoustic waves at a frequency of 25 kHz into the test part and a separate element receives the sound. The sound propagates in a plate wave mode across the test piece between the probe tips. The probe also contains a third, nonactive, probe tip which helps balance the probe on the part. The return signals are processed and the difference between the effects of good and bad areas of the part along the sound path are analyzed and compared. A complex wave front is generated internally in the material as a result of velocity characteristics, acoustical impedance, and thickness. The time and amount of received energy is affected by the changes in material properties, such as thickness, unbonds, and discontinuities. One model instrument processes and outputs changes to a set of headphones. Since the human ear is acutely aware of even subtle changes in the audio spectrum, the operator can detect and locate changes in material conditions as indicated above. Another model instrument processes the received impulse and displays the received information on a phase and amplitude motor. Another instrument uses a phase/amplitude display and the alarm can be set either on amplitude only or on phase and amplitude. The amplitude will be larger over the unbond as the motion of the plate or layer is restricted over a bonded joint and energy is lost into the base material. The impulse mode frequency range is from 2.5 to 200 kHz with most applications being performed at 5 to 25 kHz for nonmetallic composite structures. Table 13 lists some bond testing equipment.

TABLE 13. TESTING EQUIPMENT

EQUIPMENT TYPE	TRADE NAMES
LFBT (Dry coupled)	Sondicator series, S-3 AUDIBLE, Bondmaster, Zeteo, etc.
HFBT (Wet coupled)	Fokker 67, 70, 80, and 90, Bondascope 2100, Laminar 2000, 210 Bondtester, Bondmaster, etc.
PE/TTU	Branson USL38 and USL48, KrautKramer USN50 DME, USK7, USD10, DuPont Benchmark, Quantum, Sonatest UFD3A, 310D, CL3, Nortec NDT-131, DSL104, Sonic 136, Panametrics Epoch 2002, etc.
Tap test	Woodpecker WP-632 and -632F, Rools Royce Tapometer, various tap hammers as described in OEM NDT manuals.
MIA	MIA2500, MIA3000, AFD1000, Bondmaster, AD-421 M, etc.
X-ray	Sperry/Staveley, Eresco, Fedrex, Andrex, Baulteau, Phillips, Baulleau, Raymax, X-IT, Siefert, etc.
IR/Thermography camera	Inframetrics, Agema, Land, Barnes, Thermo Tracer, etc.
Eddy sonic	Harmonic Bondtester, Uniwest US-5200C, etc.

Note: Bondmaster has three technique methods in one instrument.

8.5.3.3 Pitch/Catch Swept Test Method.

This method also uses a dual element, point-contact sonic probe. One element transmits a burst of acoustical energy into the test part while a separate element receives the sound propagated across the test part between the probe tips. The swept frequency is from 20 to 40 kHz or 30 to 50 kHz, and can be set to have any start or stop frequency within the range. The frequency of the probe transducer is selected relative to the skin layer thickness and the stiffness of the material. The thinner the layer, the higher the probe frequency should be for best sensitivity. The frequency of the probe is proportional to the acoustic impedance of the layer. Materials such as graphite or fiberglass with low impedance require lower frequency probes than metal skin layers. Because the plate or lamb waves are attenuated by coupling into a second layer in well bonded joints, those signals will yield low amplitude signals. In an unbonded region the waves travel in the plate with very little attenuation or leakage into the backing material and a much larger signal pattern is displayed.

8.5.3.4 Eddy Sonic Test Method.

In this method the bond tester operates at an inspection frequency between 13.6 and 14.2 kHz depending on the panel being evaluated. No couplant is required on the surface of the part. Because the energy is generated by a pulsed eddy-current input, the parts tested are normally made from aluminum (either laminate or honeycomb).

The bond tester is sometimes referred to as the harmonic bond tester or HBT. It is capable of detecting both near-side and far-side disbonds. Other types of flaws which can be detected include crushed and/or fractured aluminum core. The response of the HBT is dependent upon specific composite structure (face sheet thickness, core cell size, and core density), defect type, and location. It can also be used to detect corroded core and disbonds under perforated skins on aircraft engine inlet ducts. The test probe contains an eddy-current driver coil and a sonic receiver centered in the eddy-current coil. The pulsed eddy current causes the unbonded layer to resonate at a frequency which is detectable by the sonic receiver. This method is most useful for inspection of aluminum honeycomb parts.

8.5.4 High-Frequency Bond Testers Theory of Operation.

High frequency bond testing (HFBT), often referred to as resonance testing, is similar in application to contact ultrasonics in that a transducer with a hard wear face is acoustically coupled to the item under inspection using a liquid couplant. However, the principle of operation differs significantly from that point.

Although referred to as high-frequency bond testing, operating frequencies are typically much lower than that of traditional ultrasonics and normally range between 25 to 500 kHz. Frequency selection is dependent on the thickness and type of material to be inspected and is normally not as a function of the transducer's resonant frequency.

HFBT utilizes special narrow-bandwidth transducers, which, when coupled to the item under test produce a continuous or standing ultrasonic wave in the material. The test material, in turn, has a damping effect on the transducer, increasing its bandwidth as well as changing its resonant frequency and signal amplitude. Basically, anomalies (such as disbonds) or changes in material thickness result in changes in the standing wave pattern of the material. These changes are detected as differences in ultrasonic or acoustic impedance at the surface of the material. Acoustic impedance changes can be thought of as variations in the ability to transmit sound between the probe and the material under test. Changes in the materials acoustic impedance cause a corresponding change in the electrical impedance of the transducer. It is these electrical impedance changes that are monitored by the instrument and displayed in the form of amplitude and/or phase information on either a meter, a scope, or both.

The phase information is related primarily to the depth of a disbond or the thickness of material while the signal amplitude is predominantly effected by the relative size or severity of the condition. However, because both phase and amplitude are interrelated and each will be affected to some degree by the various anomalies encountered, it is important for the inspector to be familiar with the responses produced by these anomalies. This auditory discernment is critical to ensure accurate interpretation of the inspection results.

High-frequency bond testing (HFBT) has proved effective for inspecting multilayer metal and nonmetal laminates for the detection of disbonds as well as multi-ply nonmetallic composite structures for the detection of interply delamination. This method has also gained some acceptance for use in the detection of skin to core disbonds in honeycomb structures; however, the aircraft manufacturer should be referred to for these applications.

HFBT is suited for inspection of materials to a maximum thickness ranging between approximately 0.25 to 0.50 inch depending on the material type and the instrument/probe combination used. HFBT provides reliable detection of disbonds and delaminations with diameters of 0.50 inch or greater. Depending on the material type, its thickness, and the nature and depth of the flaw, smaller flaws may be discovered. HFBT can also offer advantages over pulse-echo ultrasonic methods when inspecting noisy or highly attenuative material. This is due in part to the lower operating frequencies combined with reduced confusion sometimes experienced when interpreting pulse-echo A-scan presentations.

As with other contact ultrasonic methods, inspection surfaces must be relatively smooth to allow adequate acoustic coupling. This, combined with the need for a liquid couplant, can sometimes limit its application and make large area inspections somewhat tedious (and also slightly messy). HFBT can be conducted on painted surfaces; however, poor paint adhesion can increase the overall acoustic impedance of the structure and may cause erroneous indications. Poor paint adhesion may also prevent inspection due to high signal attenuation caused by this condition. It is recommended that areas exhibiting possible disbond or delamination indications be stripped of paint and re-examined to confirm any findings. Finally, when inspecting relatively thick, multi-ply composite structures, detection of a delamination in the bottom one or two plies can be

extremely difficult. This is due to the relatively small change in total material impedance seen by the probe.

8.5.5 PE/TTU Ultrasonic Theory of Operation.

The ultrasonic methods of inspection include pulse echo (PE) and through transmission ultrasonics (TTU). Both methods are based on the principal of passing a beam of sound energy through the component under test and interpreting the returned PE or received TTU signals.

The PE method utilizes either a single crystal transducer, which acts as both transmitter and receiver, or a twin crystal transducer, where one crystal acts as the transmitter and the other the receiver. The method operates on the principal of reflected sound waves, whether from the opposite side or a flaw within the component under test. The method is used mainly on monolithic structure to detect disbond and delamination conditions when access is limited to one side only. The PE method can be applied manually or by using a portable C-scan system.

The TTU method requires the use of two transducers, one transmitting the sound energy and the other acting as a receiver. Each transducer must be accurately aligned with each other on opposite sides of the component under test. This method can be used on monolithic and honeycomb structures to detect disbonds and delaminations. Any disbonds or delaminations will prevent all or part of the transmitted sound from reaching the receiver transducer.

To perform an inspection using a TTU method, both sides of the component under test must be accessible. In some instances, with special tooling, it is possible to perform an inspection with the component in situ. TTU inspections can be performed by using wet or dry coupled transducers. When relatively large surface areas are involved, the use of dry coupled roller transducers can be considered.

Inspections may be performed off the aircraft with the component immersed in a water tank or positioned between water jets. The transducers, which are not normally in contact with the component being inspected, are mounted on fixtures that automatically maintain alignment while scanning the entire inspection surface.

The inspection and interpretation can be improved through the use of a C-scan system which would provide

- controlled calibration.
- section mapping.
- layer mapping.
- three-dimensional mapping.
- enlargement of critical areas.
- high sensitivity.
- storage and retrieval of results.

Ultrasonic inspection is a fast, reliable nondestructive testing method. A schematic is shown in figure 51. Because ultrasonic techniques are basically mechanical phenomena, they are particularly adaptable to the determination of structural integrity of engineering materials. Their principal applications consist of

- flaw detection,
- thickness measurement, and
- evaluation of the influence of processing variables on the specimens.

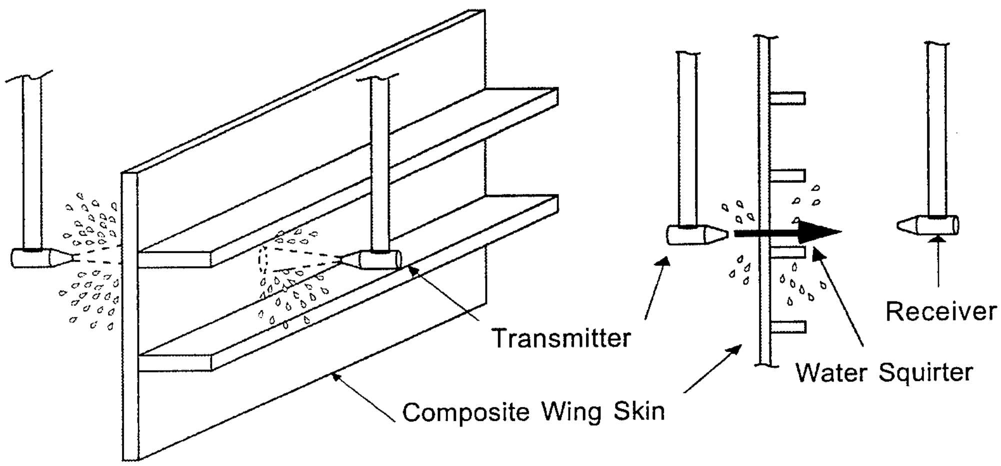


FIGURE 51. ULTRASONIC TESTING

There are many factors which limit the application of ultrasonic inspection. Among the most important are sensitivity, resolution, and noise discrimination.

Sensitivity is the ability of the instrument to detect the small amount of energy reflected from a discontinuity. Resolution is the ability of the instrument to detect flaws lying close to the test surface to separate and distinguish the indications of several defects occurring close together. Noise discrimination is the capacity of the instrument to differentiate between signals from defects and other unwanted noise of either electrical or acoustical nature. These variables in turn are affected by others such as frequency and pulse energy. For example, when frequency is increased, the sensitivity increases. With the increase of sensitivity, smaller abnormalities within the material will become detectable and this will increase the noise level thus hindering signal discrimination. With an increase in pulse energy, material noise will increase and resolution will decrease. In addition, the geometry and condition of the test material may limit the application of ultrasonic testing. Size, contour, complexity, defect orientation, and undesirable internal structure such as porosity, inclusion content, core materials, or fine dispersed precipitants all play a role in the accuracy of the inspection. Problems concerning surface toughness and scanning also limit applications for ultrasonic inspection.

Ultrasonic NDI techniques are widely used for quality control and flaw detection in composite laminates. The technique is based on the attenuation of high-frequency (1 to 30 MHz) acoustic

waves passing through the composite part. The attenuation is generally a result of three causes—dispersion due to viscoelastic effects in the resin matrix, geometric dispersion due to the heterogeneity in the composite material, and geometric attenuation due to internal defects such as delaminations, porosity, and fiber and matrix cracks. Surface roughness and the shape or contour of the test specimen also affect the wave attenuation. A summary of ultrasonic NDT methods is compiled in figure 52.

METHOD	CONTACT	IMMERSED	SQUIRTER
Pulse Echo		Water	
Through Transmission	Pulser Receiver		
Reflector	Not Applicable	Reflector Plate	Not Applicable
Resonance Impedance		Not Applicable	Not Applicable

FIGURE 52. NONDESTRUCTIVE ULTRASONIC INSPECTION METHODS

The ultrasound is generally transmitted and received by ultrasonic transducer in a pulse-echo or a through-transmission mode. The pulse-echo technique can be applied to both immersion and contact test set-ups, while the through-transmission method generally applies only to immersion and squirt test set-ups. In the pulse-echo mode, the ultrasound is transmitted by a transducer and the reflected signal is received by the same transducer after the signal is reflected from the back surface of the composite part. The attenuation of the reflected pulse is influenced by the presence of internal defects in the part, while the time delay of the reflected pulse is related to the depthwise location of defects in the composite part.

In the through-transmission mode, two transducers are used—a transmitting transducer on one side of the specimen and a receiving transducer on the other side of the specimen. The difference between the transmitted and the received pulse amplitude is related to the internal defect.

Records of ultrasonic inspections can be obtained in many forms. An amplitude versus time display for a specific point on the specimen, is called an A-scan. A display of the depthwise

location, corresponding to a gated amplitude response along a scan line, is called a B-scan. B-scan equipment displays a long-persistence cross-sectional view of the test specimen and the discontinuities (flaws) within it. C-scan equipment displays the discontinuities in a plan view but provides no flaw depth or orientation information. A permanent test record is commonly obtained on chemically-treated paper. C-scan images can be displayed either in a binary form (go/no-go indication) or in gray-scale form.

The pulse-echo technique may be used in an immersion mode of testing, but it is usually used with the contact mode of testing. In the contact method, the transducer is usually held in contact with the part surface by hand and is coupled to the part by a couplement such as water, glycerine, or other suitable liquid or semiliquid. The pulse-echo method of ultrasonic inspection usually uses longitudinal acoustic waves. Since hand scanning methods usually do not lend themselves to the recordings necessary for B- or C-scans, the contact pulse-echo ultrasonic method is normally used for an A-scan record. This mode displays the amplitude of the returning signal as a function of time. From this display, information regarding the presence and the depthwise location of the defect can be obtained.

When the contact pulse-echo ultrasonic NDI technique is used, only one-side access is required for an integral laminate. Inspection of honeycomb constructions will require access from two sides for either face sheet. The disadvantages in using this technique include the need for reference standards, experienced inspection personnel, couplement, and a clean surface. The method is also slow due to the point-by-point interrogation.

Ultrasonic inspection using the through transmission method is usually conducted with water as the couplement. Two methods of coupling the acoustic wave to the composite part can be used: (1) the immersion method and (2) the squirt method. When using the immersion method, the part and the transducers are submerged in water. The squirt method employs dynamic water columns that are squirted at the part, while the transducers and the part are suspended. In both situations, water acts as the medium that transmits the ultrasound into and out of the part.

This NDI technique is amenable to automation. It is faster and more accurate than hand-scanning, and it produces a permanent record of the inspection results. The primary disadvantage is the need for parts to be removed from the aircraft in order to be inspected. Ultrasonic test equipment is normally not portable.

The Fokker Bondtester is widely used for nondestructive inspection of adhesive-bonded constructions. It has been most effective for use with metal-to-metal adhesive bonds. Some limited success has also been noted for bonded aluminum honeycomb sandwich structures; unbonded (void) areas can be detected consistently.

To utilize such an instrument, the unit is first calibrated using bonded specimens of known quality. Tensile shear strength is generally used for metal-to-metal bonds and flatwise tensile

strength for honeycomb sandwich bonds. The quality of the bond is then determined by the magnitude of the resonance frequency shift (A-scale) and/or the damping of the peak amplitude.

8.5.6 Tap Test Method Theory of Operation.

Tap testing (see figure 53) is a manual method wherein a small diameter rod or hammer with a spherical tip is used to tap the part surface while the human ear is used to monitor the audible results. The audible sound resonating from the part will be characteristic of the mass, cohesive stiffness, and the cross-sectional thickness of the part or assembly. Complete separations caused by voids, disbonds, or delaminations create a change in cohesive stiffness resulting in an audible change of tap impact. The characteristics of the impact are dependent on the local impedance of the structure and on the mass of the tapper used.

Each tap excites a range of frequencies in the structure, some of which are audible. When a defective area is tapped, the higher structural vibration modes are not excited as strongly as when a sound area is tapped. The sound produced has less high-frequency content and the structure sounds duller.

The resonance characteristics of the part are affected by part restraint. This means that a small panel clamped to a bench will produce a lower tap sound than one held In the hand. This is due to the lower frequency modes that are excited when the added mass of the bench is attached to the part.

While a coin has often been employed to tap many parts, manufacturers of large aircraft specify a tap test tool that consists of a rod or hammer. Electronic tap test instruments are sometimes used. Some of these instruments measure the duration of impact while others measure the frequency content of the tap signal.

Tap testing is most effective on honeycomb structure with thin face sheets. Larger voids are detectable under thicker face sheets. On solid laminate structure, tap testing should be used with caution.

Tap testing is suitable for use on repairs, but care must be taken to recognize the tap sound caused by core splices, potted areas, doubler plies, surfacing compound, and other features common in repairs.

For guidelines on tap testing see the manufacturer's NDT manual for your airplane.

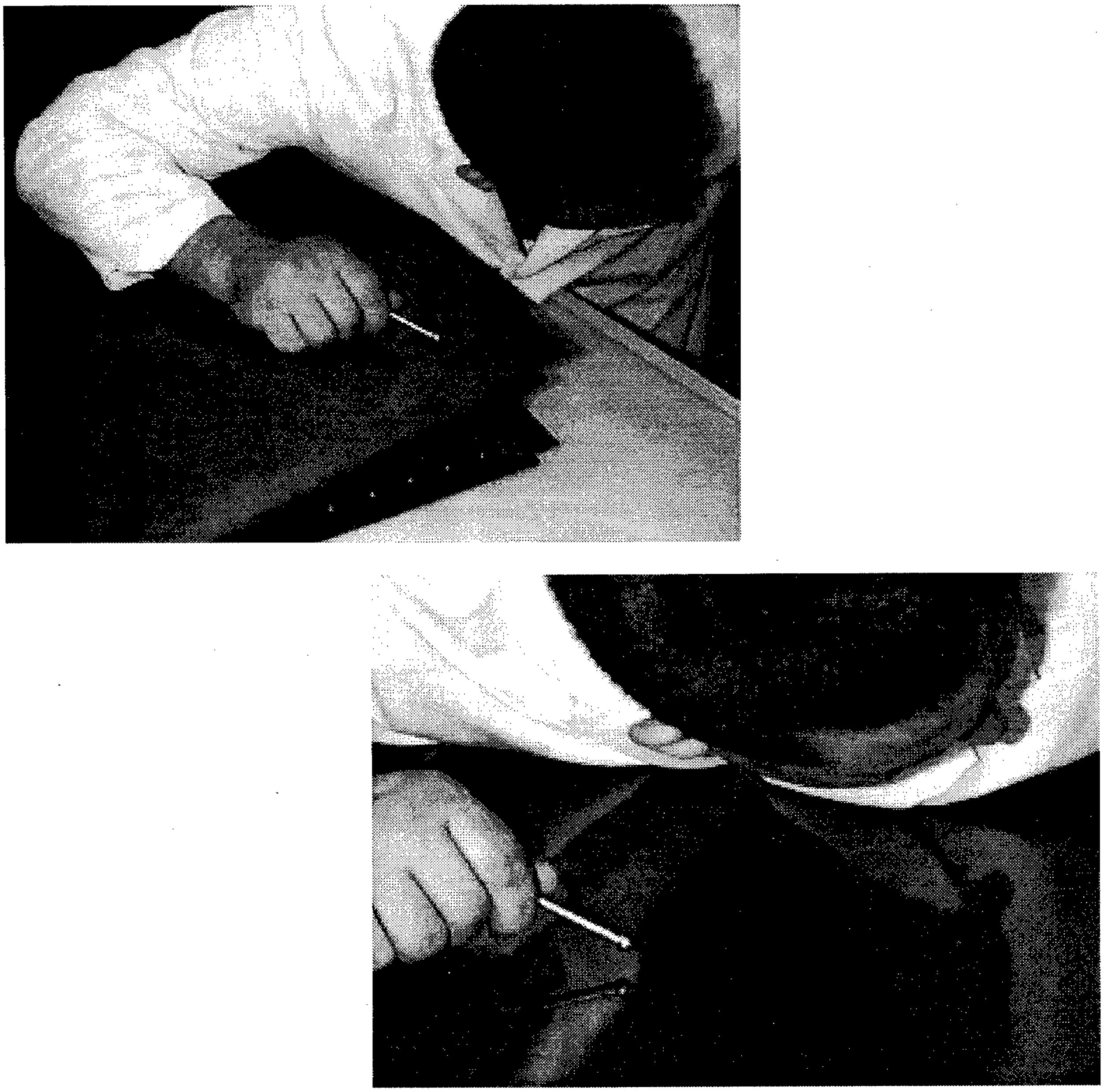


FIGURE 53. TAP TESTING A COMPOSITE PANEL

8.5.7 Mechanical Impedance Analysis Inspection Theory of Operation.

Mechanical impedance analysis (MIA) is the method of bond testing that compares the stiffness of the structure in contact with the probe tip. The stiffness of bonded structure is a function of thickness, geometry, elastic variables, and densities of the bonded components. In a bonded structure under test the component is vibrated. Disbond normally causes a reduction in mechanical impedance (stiffness) and can result in a phase or amplitude change to the displayed signal, depending on the frequency of the probe.

The probe consists of two piezoelectric crystals. The driver converts electrical energy into sonic vibrations and the receiver converts the modified vibrations into electrical signals for processing by the instrument.

If the probe is placed on an infinitely stiff structure and the driver crystal is set to vibrate at a given frequency, then the receiver crystal will compress and expand in opposition to the driver crystal (180 degree phase shift) at maximum signal amplitude. If the probe is now placed on an infinitely unstiff structure (free air) and the driver set to vibrate at a given frequency, then the receiver crystal will simply move back and forth in space but will not be compressed or expanded and thus produce no output. Somewhere between these two extremes lies reality and in general a defect will produce a signal containing amplitude proportional to its stiffness with a possible phase change. Some instruments use a continuous frequency or twin frequency mode of excitation, generally between 1 and 10 kHz. Others employ a carrier that supplies bursts of energy at two cycles per second dependent on probe type (5.7, 14.5, and 32 kHz). The MIA instruments that can operate in a twin frequency mode offer a more sensitive inspection. This is achieved through the ability to map the boundaries of real defects, which may be more complex than those in manufactured test standards.

The displayed information can be impedance plane (flying spot), meter deflection, or horizontal bar graph. Alarm thresholds can be used to provide audible or visual warnings.

In MIA inspections the structure under the probe is being resonated. Mechanical vibrations from nearby equipment can cause extraneous noise which may be displayed by the instrument. The probe itself can, by tilting in its outer case, cause spurious signals through juddering over the structure at a frequency that the instrument interprets as significant. The inspected structure can, through resonance, set up harmonic frequencies which are known to be a cause of spurious signals.

8.5.8 Radiographic Inspection Theory of Operation.

Radiographic inspection is performed by transmitting an X-ray beam through the part and usually onto film. The unabsorbed radiation exposes the film emulsion similar to the way that light exposes photographic film. The film produces a latent image that is processed to form a visible image which is called a radiograph. The radiograph is then studied for the information sought. The radiograph is an orthographic projection or essentially a shadow picture of the part. Variations in density, thickness, and composition of the part being inspected cause variations in the developed film image density. A change in density can be caused by a change in part thickness, cracks, porosity, crushed honeycomb core, or variation in the part composition such as the presence of fluid on the honeycomb or foreign material inclusion. X-ray inspection techniques vary from part-to-part, but typical nonmetallic composite structure X-ray techniques should generally use the lowest practical kilovoltage. Milliampere-second settings should be used to control film density. Ideally, film densities should be held to 1.5 to 3.0. X-ray equipment for inspection of aircraft composite structures should be a portable X-ray generator tube having a

focal spot size as small as possible and have an inherent filtration of 1.0 mm beryllium equivalent or less.

When performing an X-ray exposure the generator should be positioned so that the source to film distance (SFD) is as great as possible. At low kilovolt settings a wide variety of film speeds can be used and still achieve a high-quality image. Typically a medium-speed fine grain, high contrast film should be acceptable. Image quality indicators (IQI) are not generally available or used for composite structure. Automatic film processing is normally used for developing the film although hand developing can be used. A high-intensity film viewer should be used with low background lighting when evaluating the radiograph.

Persons that use X-ray equipment must refer to the approved organizations for the safe operation of the facilities and equipment.

In radiography, the internal structure of a solid material is visualized by exposing the sample to a source of penetrating radiation and recording the shadow image on a photographic film or plate placed on the opposite side of the sample. Most composites are nearly transparent to X-rays so low-energy rays must be used. In some instances, an opaque penetrant is needed to detect many defects. An internal void or gap decreases the amount of solid material through which the radiation passes and thus increases the intensity of the radiation reaching the film (plate) at a position corresponding to the void location. The resulting darker area of the film indicates the outline of the defect and depending on the degree of darkening of the film provides an estimate of the thickness (depth) of the void/gap. A schematic diagram of components of radiography testing is shown in figure 54.

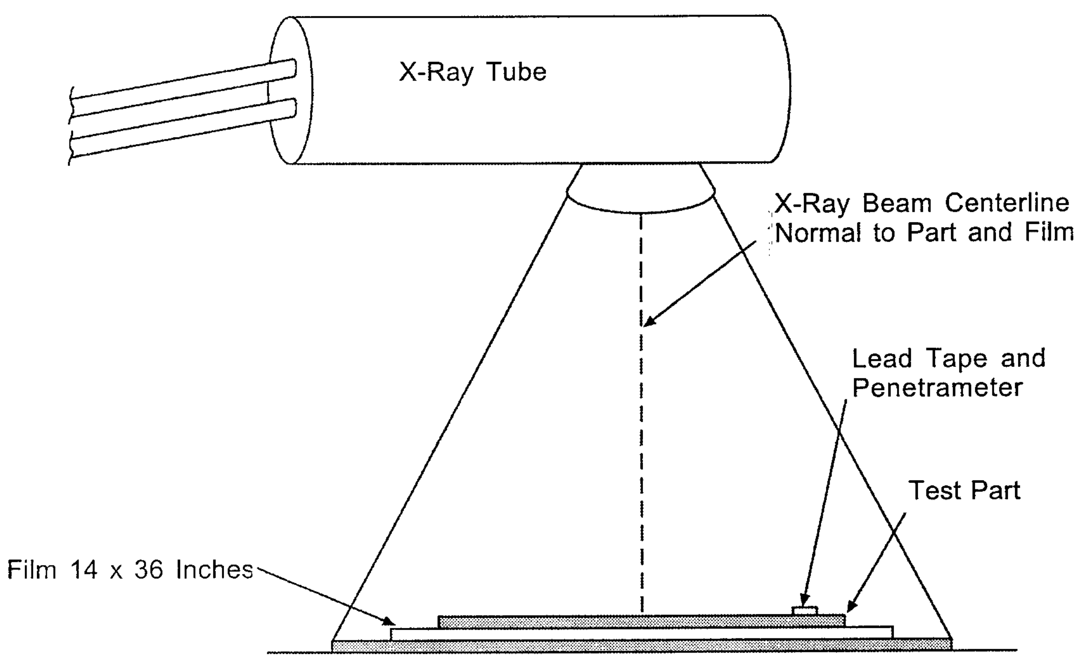


FIGURE 54. RADIOGRAPHY TESTING

X-ray inspection is the most widely used penetrating radiation method of NDT. The location of defects depends upon variations in thickness and/or density in the path of the radiation. Areas of lower density within the specimen will absorb less radiation so that the detector (film or plate) will show a stronger reaction in the corresponding area. Because plastics are of lower density than most metals the presence of a metallic inclusion such as a foreign contaminant can also be observed.

Radiography has been employed for locating large voids, delaminations, and cracks in reinforced plastic parts. Such defects can be observed provided the defect is sufficiently large with respect to the direction of the radiation path. Defects oriented normal to the radiation are often difficult to detect.

When a metallic or fiberglass composite substructure is present where a composite part is being inspected, neutron radiography is superior to X-ray radiography in the detection of flaws in the composite part or in the adhesive bondline. Metals and fiberglass are opaque to X-rays while they are relatively transparent to neutrons. This results in recordable differing absorption coefficients in defective composites at the test energy levels used for neutron radiography. Also, neutrons are sensitive to hydrogen, and corrosion caused by moisture absorption can be readily detected using neutron radiography. But neutron radiography is more expensive and the required safety precautions are more stringent compared to X-ray radiography.

Radiographic inspection lends itself to easy interpretation because of the picture-like quality of the results. It offers unique advantages while examining honeycomb assemblies because it can detect core damage and entrapped moisture normally undetected by other methods. The method also lends itself to real-time inspection techniques, thereby providing immediate results.

As a precaution, it must be noted that any of the body tissues may be injured by excessive exposure to X-rays or gamma rays. Exposure may be caused by the beam from the X-ray tube target or by scattered radiation. Operators should always be protected by sufficient shields containing lead or other equivalent materials. Maintaining a minimum distance from the X-ray source is always helpful. Gamma rays may be very penetrating and require a combination of distance and protective material for safety. Neutron bombardment can result in harmful quantities of residual radioactivity. Therefore, thick concrete walls are likely to be used as a protective shield rather than the lead plates used with X-ray radiography.

Some improvement in resolution has been achieved by using a stereovision technique where the X-rays are emitted from dual devices which are offset by about 15 feet. When viewed together, these dual images give a three-dimensional view of the material.

8.5.9 Thermography for Fluid Ingress Theory of Operation.

Thermography is a nondestructive inspection method that uses thermal gradients to analyze some physical characteristics such as internal defects. This is done by converting a thermal

gradient into a visible image using a thermally sensitive detector such as an infrared camera or an infrared viewer or a thermally sensitive film material.

All surfaces, whether natural or artificial, emit infrared (IR) radiation. The warmer the surface the more infrared energy is emitted. Emissivity is the ability of a surface to emit radiant energy usually in the infrared wavelength. Thermography cameras use infrared detectors in one of three varieties. When the camera observes a thermal difference and the inspection surface has a constant emissivity, then usually the reason is because of a temperature change. The thermal image captured using an IR camera will normally be in the form of a colored map, showing a constant background of the surrounding surface area. The map depicts temperature variations as a quite distinctive and contrasting color. The human perception attempts to interpret the infrared information as a visual image. The key to performing a thermographic inspection is to forget visual and think heat. Much the same as light, IR can be emitted, transmitted, and reflected.

The ability of the surface to emit, reflect, or transmit infrared varies widely with the nature of the material. Usually, natural and organic surfaces are very good emitters, poor transmitters, and poor reflectors. Good transmitters, including germanium, sapphire, and some plastics (e.g., polyethylene and polypropylene) are opaque to visible light. However, most surfaces are opaque to IR energy. Modern thermal imagery can detect small changes in radiant energy over long distances.

There are five factors that affect thermographic inspections.

- Inspection surface temperature
- Inspection surface emittance
- Inspection surface reflectance
- Background or ambient temperature
- Quantity of energy producing the thermal difference

A good IR radiator has a high emittance value while a good IR reflector can be used as a mirror. From a practical point, the background temperature plays little in the equation if the inspection surface is in close proximity to the detector and the relative humidity is low. The thermographic image is dependent upon all these relative values.

Fluid ingress can be accurately detected in nonmetallic composite honeycomb structure using thermography providing that a few simple rules are adhered to.

- A thermal change in the structure must be provided to the mass of fluid as an energy absorption path. This can be as an external heat source (i.e., electric heater blanket) or as an external cooling medium such as is supplied naturally during aircraft flight.

- The internal thermal difference must be apparent at the inspection surface.

- The inspection surface should be within a few degrees from perpendicular to the line of sight.

- The surface, suspected of containing fluid, should be inspected before thermal equilibrium occurs but after any structural effects have been absorbed.

8.5.10 Less Common NDT Methods.

The development of the new nondestructive testing equipment is proceeding rapidly. However, the progress in adapting these new techniques and equipment to reliably solve aircraft field maintenance inspection problems is somewhat lacking. This is probably due in part to the application of these new processes. Among new areas of development for aircraft application are the following.

8.5.10.1 Acousto-Ultrasonics.

This method of analysis is similar to ultrasound except that a separate sensor sends the signal and another receives the signal. However, both sensors are located on the same side of the sample so a reflected signal is detected. This method is more quantitative and portable than standard ultrasonic.

8.5.10.2 Acoustic Emission (AE).

In this method, the sounds emitted by a sample are detected as the sample is subjected to a stress. In actual practice, thermal stresses are the most commonly employed though mechanical stresses may also be utilized. This method holds great promise but quantitative interpretation is not yet possible except for well-documented and simple shapes such as cylindrical pressure vessels.

8.5.10.3 Optical Holography.

The use of laser photography to give three-dimensional pictures is called holography. This method can detect flaws in composite samples by employing a double-image method where two pictures are taken with an induced stress in the sample between the times of the pictures. In the past, this method has had limited acceptance because of the need to isolate the camera and sample from vibrations. However, a new phase locking technique seems to eliminate this problem. The stresses that are imposed on the sample are usually thermal. If a microwave source of stress is used, moisture content of the sample can be detected. This method is especially useful for detecting debonds in thick honeycomb and foam sandwich constructions. A related method is called shearography. In this method, a laser is used with the same double exposure technique as in holography with a stress applied between exposures. However, in this case an image-shearing camera is used in which signals from the two images are superimposed to give interference and thereby reveal the strains in the samples. Because strains are detected, the size of the pattern can

give an indication of the stresses concentrated in the area, and therefore, a quantitative appraisal of the severity of the defect is possible. This attribute, plus the greater mobility of this method over holography, and the ability to stress with mechanical, thermal, and other methods, have given this method wide acceptance in a relatively short period of time since its introduction. A summary of nondestructive test uses is shown in table 14.

TABLE 14. NONDESTRUCTIVE TEST USES

METHOD	STRUCTURE	DEFECTS DETECTED
Visual	All	Surface damage
Tap test	All	Delaminations near surface
Ultrasonic	Laminate	Delaminations
Resonance	Thin laminate	Delaminations
Bond testers	Bonded	Disbonds
X-ray	All	Water in honeycomb
Shearography	All	Disbond/delaminations
Thermography	All	Disbond/delaminations
Ultrasonic	All	Porosity Voids Delaminations Lack of bond Resin rich Resin starved Existence of foreign material
Resonance bond testers	Cocured bonds Adhesive bond	Lack of bond Voids Delaminations Foreign material
Resonance (Tap test)	Sandwich	Lack of bond Void Delaminations Lack of tie-in at closure Lack of tie-in at core splice Blown core
X-ray	Honeycomb sandwich laminate corners	Node separation Condensed core Foreign material Crushed core Delaminations

8.5.10.4 Infrared.

Utilization of infrared energy as a nondestructive technique has recently received attention. Infrared has been used in chemical analysis but the use of these techniques to verify the integrity of components is new. These techniques capitalize on the fact that heat is either generated by or can be induced into anything. One interesting use of this application is the evaluation of the condition of electrical or electronic components. By knowing the heat generated by a sound efficient contact, one can predict the life expectancy of any similar contact simply by measuring the heat generated from the contact being evaluated.

These nondestructive inspection liquid crystals are in a slurry form or embedded in tape. This tape or slurry is applied to the surface of the part being inspected. The temperature change in the part will cause the liquid crystal to change color. Some applications include checks for delaminations in honeycomb materials and location of hot points or overheating in electronic devices.

In recent years efforts have been combined to expand the detection capability of radiography with color film. Two basic systems for the color enhancement have been developed. One is the photographic system and the other is an electronic system. The photographic method is a laboratory technique and offers a greater resolution or sensitivity than the electronic system. The electronic system is commercially available, provides real time immediate film processing, and is an automatic system.

Both systems offer greater resolution in film interpretation than the standard back lighting process (illuminator or zoom lens) for black and white film. Color enhancement eliminates the various shades of gray on the film and provides for a faster, earlier, and more accurate interpretation of the film.

8.6 DESTRUCTIVE TESTS.

8.6.1 Objective.

The goal of destructive testing is to supplement nondestructive testing to assure the structural integrity of composite parts. As more complex composite parts are used, destructive testing provides a means of examining areas not adequately inspected by other methods. Destructive tests of first articles can be used to verify structural concepts, tooling, and fabrication processes. Destructive testing is necessary when nondestructive inspection is not sufficient to assure part quality and there is potential for undetectable manufacturing defects. For more complex composite configurations, nondestructive inspection cannot adequately inspect all features of the part. Use and selection of destructive testing is illustrated in figure 55.

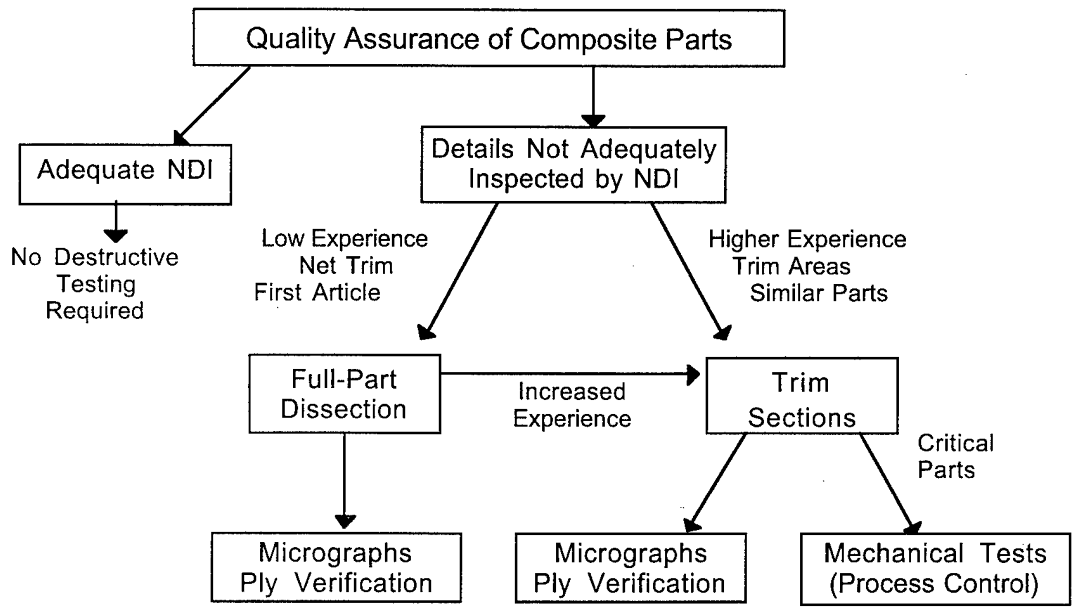


FIGURE 55. USE OF DESTRUCTIVE TESTS

8.6.2 Destructive Test Approaches.

There are two primary categories of destructive tests: dissection of the full part or examination of trim section of the part. Full dissection, generally done for the first part from a new tool, gives a complete examination of the part but is expensive to perform. Examination of excess trim sections is the preferable approach whenever possible. The part is not destroyed, structural details can still be examined and mechanical test coupons can be obtained.

8.6.2.1 Full-Part Dissection.

Full-part dissection is the approach often envisioned when the term destructive testing is mentioned. Since it prevents future use of the part, full-part dissection should be reserved for parts that meet the following criteria:

- Areas cannot be adequately inspected by NDI.
- Part is complex and there is a low experience level for working with the structural configuration of fabrication process.
- Part is net trim; detail areas of interest cannot be examined using excess trim areas of part extensions.

8.6.2.2 Trim Sections.

Examination and testing of trim sections offer a balance of quality assurance and cost. Trim sections can be part extensions that are intentionally designed to go beyond the trim line or can be taken from cutout areas inside the part. Section cuts from detail areas can be examined for discrepancies. Test coupons can be machined from the sections and mechanically tested to ensure the structural capability of the part to verify quality of the fabrication process. Using coupons in this way can satisfy destructive testing requirements and process control requirements. Other tests include determination of fiber volume.

8.6.3 Implementation Guidelines.

The frequency of destructive tests are dependent on part type and experience. If the producer has significant fabrication experience, complex parts may not require periodic destructive testing, but only a first article dissection. For low experience with complex parts, periodic inspection with increasing intervals may be preferable. Critical (safety of flight) parts warrant consideration for destructive testing.

Examination and testing of trim sections can be carried out on a more frequent basis and at less coast than full-part dissection. Quality assurance can be enhanced by using more frequent and less elaborate trim section examinations.

Destructive tests should be conducted before the part leaves the factory. Periodic destructive tests monitor the manufacturing processes to assure the quality of parts. If a problem does occur, the periodic inspections bracket the number of suspect parts. Not every part series needs to be examined. If many parts reflect the same type of configurations and complexity, they can be pooled together for sampling purposes. Parts made on tools fabricated from one master splash can also be grouped together.

A typical sampling plan might include first article full-part dissection followed by periodic inspections employing dissection of trim sections. The periodic inspection intervals can vary depending on the success rate. After a few successful destructive tests, the interval can be increased, if nonconforming areas are found in destructive tests, the inspection interval can be tightened up. If problems are found in service, additional components from the same production series can be dissected to assure that the problem was isolated.

For the trim section approach, periodic destructive tests can be conducted at smaller intervals since the cost is much less. Small intervals may be especially desirable in the case of critical parts.

For first article inspection, one of the first few articles may be chosen to represent first article. Some of the reasons for not stipulating the very first structure built are (1) it may not be as representative of the production run because of lessons learned and special handling and (2) another part with processing problems or discrepancies may reveal far more information.

Potential areas and items to examine include:

- primary load paths within the part,
- areas that showed indications from nondestructive inspection,
- tool markoff near occurred details,
- ply drop offs at a taper,
- ply wrinkles,
- resin-starved and resin-rich areas,
- corner radii and cocured details,
- core to face sheet fillets, and
- tapered core areas.

8.6.4 Test Types.

Both full-part dissection and trim sections involve examination of detail areas. After machining the detail areas, photomicrographs can be obtained to examine the microstructure. Another type of destructive testing is ply verification. Only a small section is need to perform a deply or grind down to verify that the plies are laid up in the correct stacking sequence and orientation. For machine lay-up, the procedure should not be necessary after initial validation. To investigate items such as ply lay-up, potential ply wrinkles, and porosity, initial core plugs can be taken at fastener hold locations and photomicrographs can be developed.

When mechanically testing coupons that were machined from trim sections, the coupons should be tested for the critical failure mode for that part of that area of the part. Tests addressing typical failure modes are unnotched compression, open hold compression, and interlaminar tension and shear.

8.7 ASSEMBLY INSPECTION.

Laminates are prone to particular types of defects unless they are machined and drilled properly. Workmanship standards, required by manufacturer's process specifications, are needed to control the quality of trimmed edges and drilled holes. These standards established visual acceptance/rejection limits for the following typical defects: splintering, delamination, loose surface fibers, overheating, surface finish, off-axis holes, and surface cratering. Typical defects in the drilling operations are delaminations and broken fibers which start at the hold boundary. Since these defects are internal in nature, an evaluation of the seriousness of the flaws is not possible by visual inspection alone. It should be backed up by nondestructive inspection techniques. Internal defect acceptance and rejection limits must be established for nondestructive inspection.

8.8 POSTASSEMBLY INSPECTIONS.

Except for overall dimension checks and visual inspection, particularly of bolted joints, postassembly inspection does not require any specialized equipment. However, attention must be paid to areas that have been forced down to meet mating parts without proper shimming as those areas are susceptible to delaminations.

8.9 GENERAL TECHNIQUE HINTS.

8.9.1 General.

The inspection of composite structures is a complex task which, to be reliable, requires experience and skill. To ensure inspections are conducted with maximum effectiveness, consistency, and reliability, it is necessary that the inspector be equipped with a certain level of knowledge and have access to proper inspection equipment. It is imperative that inspectors should have a good understanding of basic fabrication and repair techniques as well as specific knowledge of the part under inspection. Additionally, inspectors must be familiar with the capabilities and limitations of the various inspection methods and utilize all of these tools when circumstances dictate. The following dialogue provides useful hints and techniques, which can assist the inspector when confronted with this task. Nevertheless, there is no substitute for a good training program and the considerable knowledge of an experienced inspector.

8.9.2 Part Knowledge.

Because of the number of variables that may be present in any composite structure and the impact that these variables can have on the inspection process, it is necessary that the inspector be familiar with the part under inspection. This information can be obtained through past experience with the part, structural repair manuals, and when available, detailed part drawings.

Using a straight edge to guide the probe helps ensure proper scan coverage and simplify interpretation by allowing scanning parallel to edges, ply drops, and other details. Probes of the same type may not have similar operating characteristics. Always recalibrate when changing probes.

Marking indications on the part surface can aid evaluation. Indications are sometimes caused by something other than a defect (such as a core splice or potted area). Signals which at first seem confusing can be identified if they are carefully marked on the part until a pattern emerges.

8.9.3 Structural Considerations.

As with any composite inspection, it is important for the inspector to be familiar with the part under test. There are several conditions that can produce disbond-like indications, thus knowledge of the part is critical for accurate evaluation. Core splices, potting, and internal doublers can produce false indications under some conditions. Careful mapping of the defect can help to identify some of these conditions and when necessary X-ray inspection should be used.

9. REPAIR.

9.1 INTRODUCTION.

As this handbook is concerned primarily with the manufacture and inspection of new aircraft parts using composites, repair of these parts is discussed only for completeness. During the manufacturing process, defects or damage can occur. The repair of these abnormalities is addressed by the quality control department with their discrepant hardware department system and repaired by the original equipment manufacturer (OEM).

Repairs to be performed while the aircraft is in service are controlled by Federal Aviation Regulations (FARs) and Advisory Circulars (ACs) devoted to the maintenance of civil aircraft. Of particular interest are FAR, Part 43 Maintenance, Preventive Maintenance, Rebuilding, and Alterations and Part 145 Repair Stations.

Part 43 and the advisory circulars associated with this part specify methods which have been approved for repair and alteration. If a repair is not already approved it must be described in the manufacturer's structural repair manual (SRM) or be given special approval by a representative of the Federal Aviation Administration. Repair station certification requirements are given in FAR, Part 145. To obtain FAA certification, a repair station must submit documentation to demonstrate the skills of personnel, inspection procedures, and the necessary facilities and equipment. AC-145-6 provides guidance on how to comply to Part 145 for repair of composites.

Repairs for structures made of composite materials are frequently similar to repairs made on metallic structures, particularly those using bolted repairs. However, certain differences exist and must be understood by repair personnel.

Typical repair processes consists of damage identification, damaged structure removal, design and analysis of repair, repair implementation, and repair inspection. Each of these steps are described in this chapter but not in great depth. For more detail and step-by-step instructions, one can consult evolving Society of Automotive Engineers (SAE) documents that are being generated by the ATA/IATA/SAE Commercial Aircraft Composite Repair Committee (CACRC). Documents available from SAE are

- ARP4483, Permanent Structural Bonded Repairs,
- ARP4844A, Composites and Metal Bonding Glossary,
- ARP4916, Masking and Cleaning of Epoxy and Polyester Matrix Thermosetting Composite Materials,

- AE-27 (AIR4928), Guide for the Design of Durable and Maintainable Aircraft Composites,
- ARP4977, Drying of Thermosetting Composite Materials,
- ARP4991, Core Restoration of Thermosetting Composite Materials, and
- ARP5089, Composite Repair NDT/NDI Handbook.

For repairing of specific aircraft parts the OEM SRM must be consulted.

Good references for more information on joints in composites can be found in MIL-HDBK-17 and *Fiber Composites Analysis and Design Handbook, Vol. II, Structures* DOT/FAA/CT-88/18 published by the FAA.

9.2 IN-PROCESS STANDARD REPAIRS.

During the manufacturing process it is possible for the completed composite part to suffer some abnormality of materials, processes, machining, or handling during the through-the-plant travel. Each part manufacturer has developed a set of Standard Repair Procedures in an attempt to correct these abnormalities or defects of manufacture.

During the quality assurance inspection procedures defects such as voids, delaminations, or disbonds are discovered which would cause the hardware to be rejected. The OEM engineering department will, in all cases, disposition the discrepant hardware to be repaired, restored to its original condition, or scrapped.

9.3 DAMAGE ASSESSMENT.

Careful assessment of damage is essential. Although the removal of all disbond, delamination, and corrosion is necessary, it is important to cut away only the minimum amount of material required to remove the damage. It is also very desirable that the cut out should be circular, elliptical, or have well rounded corners to avoid stress concentrations being introduced. Nevertheless, it is important to keep the size of the damage as *small* as possible to remain within the permitted limits. At the other extreme, there may be a case for replacing a complete skin on some occasions in preference to attempting the repair of a very large hole. Following are some of the different types of defects.

Adhesive Bond Line Defects

- Porosity
- Void

- Lack of bond
- Foreign material
- Delamination (disbond)

Laminate Defects

- Porosity
- Voids
- Delamination
- Resin rich
- Resin starved
- Foreign material
- Impact damage

Honeycomb Sandwich Defects

- Void
- Lack of bond (no fillets)
- Lack of tie-in at closure
- Lack of tie-in at core splice joint
- Blown core
- Node separation
- Condensed core
- Foreign material entrapment
- Crushed core
- Impact damage (in-service)

To find the extent of damage, several methods of inspection are available as noted in the previous section. They are listed in order of cost and complexity.

- Visual; dents, delamination, corrosion, cracks
- Tap test (coin tapping); disbond, delamination
- Ultrasonics; disbond, delamination
- Eddy currents; cracks
- X-ray; water ingress, cracks
- Thermography; water ingress, disbond

These are all nondestructive methods. Thermography is convenient but the equipment is very expensive. Inspection is an important process and the boundary of any damage needs to be defined with reasonable accuracy. In some cases cold-bonded repairs are not permitted to be as large as hot-bonded repairs. In others, repair may not be allowed beyond a certain size.

Therefore, the location of the damage in the part may determine the method of repair or whether any repair is permitted at all.

In any event, before starting on a large amount of work, accurate inspection is needed to establish what has to be done. Each method has its limitations and these need to be understood. Many parts will need inspection by two or more methods in order to check for all possible defect types. The last four methods in the list above should be carried out by NDI specialists.

After the damage is identified it must be removed carefully and the area prepared for the designed repair process. Drying the structure in the vicinity of the repair may also be necessary for core and thermosetting composites.

If the disposition is to repair the part, a very specific procedure is followed. This procedure can be a one time only or in most cases it follows processes in the Structures Repair Manual. It should be noted however that discrepancies that occur on a regular basis are investigated as to cause and corrective action is put in place to try and make sure that type of damage does not continue to occur.

After the repairs are complete the part must be inspected again to determine that the part has been restored to its initial intended structural and fit requirements.

Records of any damage and subsequent repair must be included in the documentation accompanying the part. It should be easy to see what the damage was and how it was repaired. It should also include a final quality acceptance inspection. At this point, the part is released to the next manufacturing operation, such as assembly.

Note: The OEM Structural Repair Manual is normally the basis for Depot or Line Repair procedure followed by the aircraft user.

9.4 DESIGN OF REPAIRS.

A repair has the objective of restoring a damaged structure to an acceptable capability in terms of strength, stiffness, functional performance, safety, cosmetic appearance, and service life. Ideally, the repair will return the structure to original capability and appearance.

The design assessment of a repair for a given loading condition involves the selection of a repair concept, the choice of the appropriate repair materials and processes, and specifying the detailed configuration and size of the repair. Most repairs are basically designed as a joint to transfer load into and out of a patch. To ensure that the repair configuration will have adequate strength and stiffness, the repair joint must be analyzed to predict its strength.

The selection of the type of load transfer joint to be used for a patch/strap is a tradeoff between simplicity, strength, and stiffness. The easier configurations are generally not as strong as the

more difficult ones. It is critical that the materials and process information are available prior to the system being put into place.

9.4.1 Repair Design Criteria.

Repair design criteria for permanent repairs are fundamentally those that were used to design the part that is to be repaired. These are (1) restore stiffness of the original structure, (2) withstand static strength at the expected environments up to ultimate load including stability, except for postbuckled structure, (3) assure durability for the remaining life of the component, (4) satisfy original part damage tolerance requirements, and (5) restore functionality of aircraft systems. Additionally there are other criteria applicable in repair situations. These are to minimize aerodynamic contour changes, weight penalty, load path changes, and to be compatible with the aircraft operations schedule.

Repair design criteria for temporary repairs can be less demanding, but may approach permanent repairs if the temporary repair is to be on the airplane for a considerable time. Such repairs will have only static strength limit load or maximum load in the spectrum capability and no stiffness requirements or durability goals. Such requirements reflect a one-time flight to a repair facility. If at all possible most users of aircraft and original equipment manufacturers (OEM's) parts prefer permanent repairs, as temporary repairs damage parent structure necessitating a more expensive permanent repair or part scrapping.

In commercial aircraft the design criteria are not transparent; only specific repairs for the particular damage, its size and location, are indicated in the SRM'S. However, in most instances one can be assured that the design criteria discussed in this report were followed.

9.4.1.1 Stiffness.

The first consideration in any repair is to replace structural material that is damaged. This means that the stiffness and placement of a repair patch should match the parent material as closely as possible. This avoids any recalculations of the overall dynamic behavior of the component, such as flutter or structural load redistributions. Furthermore, many lightweight flight vehicle structures are designed to meet stiffness requirements that are more critical than their strength requirements. A repair made to a structure of this type must therefore maintain the required stiffness so that deflections or stability requirements are met.

Fixed aerodynamic surfaces, such as wings and tails, are frequently designed to have bending and torsional stiffness that are adequate to prevent excessive deflections under aerodynamic loading. This is to prevent divergence and control surface (such as aileron) reversal. Moveable surfaces are frequently sensitive to aerodynamic flutter and their stiffness may have been carefully tailored to obtain natural frequencies for which flutter will not occur.

Increasing the stiffness of a control surface, especially the bending stiffness, can reduce the flutter speed to unacceptable levels and a decrease in stiffness can be equally damaging. Any significant change in stiffness must be evaluated for its effect on the dynamic behavior of structure. Stiffness can also affect the deflections of actuated doors, such as landing gear doors. Reduction in stiffness can result in excessive deflections under aerodynamic loading. These reductions may increase drag or in extreme cases cause loss of the structure.

9.4.1.2 Static Strength and Stability.

Any permanent repair must be designed to support applied loads at the ultimate design load level at the extremes of temperature excursions, moisture levels, and barely visible damage levels. If the loads are not available, specific SRM repair recommendations must be strictly adhered to. In the SRM repairs there is an implicit assumption that the specific repairs meet all static strength and stability requirements.

Load path changes are a special concern when designing repairs. When strength restoration is necessary, attention must be given to the effect of the stiffness of the repair on the load distribution in the structure. If a patch has less stiffness than the original structure, the patch may not carry its share of the load, and this causes an overload in the surrounding material. This condition can be caused by a patch made from a less stiff material or from fasteners that fail to transfer full load because of loose fits or fastener deformation. Conversely, an overly stiff patch may attract more than its share of load, causing adjacent areas to which it is attached to be overloaded. Stiffness mismatch between parent material and the patch may cause peel stresses that can initiate debonding of the patch.

Repair manuals for specific aircraft frequently zone the structure to show the amount of strength restoration needed or the kinds of standard repairs that are acceptable. Zoning permits the use of simpler repairs in areas where full-strength restoration is not necessary. Zoning also restricts operator repairs in areas where repairs are too complex and should be only repaired with OEM's involvement.

Structures loaded in compression or in shear, such as some wing skins, webs of spars or ribs, and fuselage structure, including both external skins and internal bulkheads, are stability and not strength critical at ultimate design load. Two types of failure in stability are possible.

- Panel Buckling—The panel, such as a section of wing skin, buckles between its major supports, for example, spars and ribs. The repair must account for the stiffness of the panel and the amount of support provided by the attachment to the substructure. Some portions of structure, for example wing skins, are permitted to buckle below ultimate design load. These types of structures develop specific postbuckling behavior which redistributes the load and allows the structure to carry ultimate load. Any repair of a stability critical structure and especially a structure that is permitted to buckle should be

considered in not affecting its buckling and postbuckling modes. Matching the stiffness of the parent material is of utmost importance here.

- Local Crippling and Buckling—This is buckling of the cross section of a member, such as a spar cap, by distortion of the cross section rather than the overall buckling along its length or width. Restoration of local crippling strength must be considered when making repairs to the substructure.

Composite laminates under compression load can fail when individual fibers or bundles of fibers buckle where delaminations or penetrations result in fibers with reduced support. Because of the danger of microbuckling or local ply buckling, resin injection repair that fills a delamination without adequately bonding the delaminated plies together could be unsatisfactory.

9.4.1.3 Durability.

Durability is the ability of a structure to function effectively throughout the life of the vehicle. For commercial transport aircraft the design life can be as great as 50,000 flight hours. Included among the factors affecting durability are temperature and moisture environments. Composite aircraft structures, if adequately designed to satisfy static load requirements, are usually durable. In other words, composite structures are static strength critical and not fatigue critical. This is in contrast to metal structures which are fatigue and fracture critical. This has important implications when nonpermanent repairs are considered.

Although the parent composite structure may not be durability critical, structural repairs may be more susceptible to damage caused by repeated loads during their service lives. This is because the repair process is not as well controlled and the repairs themselves create solitary joints and discontinuities in areas that are exposed.

For bolted joints, high stresses on fastener holes must be avoided as they may elongate under repeated loadings and lead to fastener fatigue. Bonded repairs should be well sealed as they can develop disbonds after being weakened by environmental effects. All found delaminations, unless specifically stated in the SRM, should be repaired, as unrepaired delaminations tend to grow under compressive or shear loading. Bolted repairs of sandwich structure must be sealed.

9.4.1.4 Damage Tolerance.

Composite structures are susceptible to damage caused by impact. Because the damage caused may not be visible, composite structures are designed to be damage tolerant. In practice, this is accomplished by lowering design strains so that the structure with impact caused damage can withstand ultimate load. The repair must also be capable of tolerating such levels of impact damage. The level of impact damage is usually established by OEM's with concurrence of a certifying agency.

9.4.1.5 Related Aircraft Systems.

In addition to satisfying structural criteria, compatibility with related aircraft systems may also be required of the repair. These systems include:

- Fuel System—Structure is frequently used to contain fuel, as in the wet wings of many aircraft. A repair must seal adequately to prevent leakage of the fuel. The repair may also be subjected to fuel pressure loadings. Repair material must be compatible with fuel.

- Lightning Protection System—Some composite structures have provisions for conducting lightning strikes by use of flame-sprayed coatings, bonded metallic strips, or wire mesh. A repair to the structure must restore the electrical continuity as well as the structural strength. Bolted repairs around fuel tanks must avoid creating an electrical path.

- Mechanical System—Components that are mechanically actuated, such as landing gear doors or control surfaces, must function correctly after repair. Clearances and fit-up to adjacent fixed structures may be critical. Rerigging or rebalancing may be required after repair.

9.4.1.6 Aerodynamic Smoothness.

High-performance flight vehicles depend on smooth external surfaces to minimize drag. During initial fabrication, smoothness requirements are specified usually by defining zones where different levels of aerodynamic smoothness are required. Most SRM's specify smoothness requirements for repairs consistent with initial part fabrication.

The most critical zone typically includes leading edges of wings and tails, forward nacelles and inlet areas, forward fuselage, and over wing areas of the fuselage. The least critical zones typically include trailing edges and aft fuselage areas. In addition, intermediate zones may be specified.

For the most critical zone, forward-facing steps are usually limited to 0.005 to 0.020 inch at permanent butt joints. At removable panels, mechanical doors, and major joints, forward-facing steps from 0.010 to 0.030 inch are typically specified. On installed equipment, such as antennas and navigation lights, steps up to 0.020 to 0.040 inch are permitted. All sharp edges resulting from patches or ply terminations should be smoothed and feathered.

Whatever the requirements, each exterior repair should restore aerodynamic contour accurately and smoothly as structurally and economically feasible. Trade-offs exist between accepting a slight reduction in performance in order to accept a repair that is more structurally sound and that is easier and quicker to accomplish.

9.4.1.7 Weight and Balance.

Compared to the overall weight of the vehicle, the weight added by most repairs is insignificant. Exceptions may exist for very large repairs or for space vehicles. The weight of repair becomes a major concern when the repair changes the mass balance of components sensitive to dynamic response such as moveable control surfaces, rotor blades, and rotating shafts. In such cases, it may be possible to remove as much damaged material as will be added by the repair so that there is little change in weight and moments of inertia. If that is not possible the part must be rebalanced after repair.

9.4.1.8 Cost and Schedule.

Wherever possible, repairs should be made within reasonable time and cost limits. A trade-off exists between repairing a component and replacing it. Except for very simple inexpensive parts, experience has shown that if the capability to repair exists, it is almost always less expensive to repair the component than to replace it. Costs and schedules are influenced by several factors as listed below:

- Downtime—The time required to make a repair is an indirect cost because the vehicle is out of service while the repair is being made. For commercial use, downtime is a cause of lost revenue and hence this factor is of the utmost importance. For military use, downtime represents a loss of operational readiness. In general, it is desirable to make the necessary repair in as short a time as possible.

- Facilities and Equipment—Repair procedures that require expensive facilities or special equipment increase the cost of the repair. Examples include autoclaves for high-pressure cures of bonded repairs; air-conditioned rooms for environmental control of temperature, humidity, and cleanliness; and special fixtures.

- Skill Level—Training and compensation for any specialized skills contribute to repair cost.

- Materials—While the direct cost of materials used in a repair is normally a small part of the total cost, significant indirect costs can result from special handling requirements such as storage, safety, process control, procurement, and waste. Availability is a significant factor in material selection.

9.4.1.9 Operating Temperatures.

Most flight vehicles experience extremes of temperature during use. Repairs to such flight vehicles must be acceptable for the temperature extremes for which the vehicle was designed. Low temperatures result from high-altitude flight or from extremes of ground storage in cold climates. Many aircraft are designed for a minimum service temperature of -65°F (-54°C).

Elevated-temperature requirements vary with the type of vehicle. The maximum temperature for commercial transport aircraft and most rotary wing vehicles is 160°F (71°C) and generally occurs during ground soak on a hot day. However, components experiencing significant loads during takeoff and initial climb may require validation of design ultimate loads at temperatures up to 200°F (93°C). Supersonic transport, fighter, and bomber aircraft typically experience aerodynamic heating of up to 220°F (104°C) or in special cases as high as 265°F (130°C), especially on the leading edges of lifting surfaces. Components exposed to engine heat, such as nacelles and thrust reversers may be required to withstand even higher temperatures in local areas.

Operating temperatures influence the selection of repair materials, especially adhesives for bonded repairs. Materials that develop adequate strength at the required temperature must be selected. The combination of temperature extremes with environmental exposure (especially moisture) frequently is the critical condition for which the repair must be designed.

9.4.1.10 Environment.

Repairs may be exposed to many environmental effects, including those listed below:

- Fluids—salt water or salt spray, fuel or lubricants, hydraulic fluid, paint stripper, and humidity.
- Mechanical loading—shock, acoustic or aerodynamic vibration, and operating loads.
- Thermal cycling—ground to air changes in temperature, engine heating.

Moisture is particularly critical to the polymeric matrix composites. At elevated temperatures, absorbed moisture reduces the ability of the matrix to support the fibers, thereby reducing the strength of the laminate for compressive or shear loading. This effect is considered in the original design, and allowable loads are frequently limited by hot-wet conditions. The same considerations pertain to bonded repairs.

Absorbed moisture can effect bonded repairs in three ways. These must be considered in the selection of a repair procedure.

- Parent Laminate Blistering—As a wet laminate is heated to cure a bonded repair, the absorbed moisture may cause local delaminations or blisters. Prebond drying at lower temperatures, slow heat-up rates, and reduced cure temperatures all diminish the tendency to blister.
- Blowing Skins of Sandwich Structure—Moisture in the cells of honeycomb sandwich structure expands when the part is heated to cure a bonded repair and develops sufficient

pressure to separate the skin from the core, especially if the strength of the adhesive has been reduced by temperature and moisture. Predrying is normally used to prevent bond line failure of this type.

- Porosity in Bond Lines—As a repair is bonded to a wet laminate, the moisture tends to cause porosity in the bond line. This porosity can reduce the strength of the bond line. This problem can be minimized by predrying, reduced temperature cure, and selection of moisture-resistant adhesives.

9.4.2 Analysis of Repairs.

Nearly every repair consists of a patch of some kind and a joint through which the loads are transferred into the patch. Joints are basically either bonded or bolted or a combination of these. Analytical procedures for bonded and bolted joints tend to be complex and require computer programs for their solution.

All analysis procedures use adhesive properties in their computations. Caution must be used in selecting the correct properties. Analysis procedures for bolted and bonded repair joints are described in MIL-HDBK-17E.

Selected procedures that represent typical generic repairs are given for monolithic skins, honeycomb sandwich structures, and substructures. There are numerous variations of these procedures for specific situations. While it is not practical to cover all variations in this handbook, personnel who are responsible for making repairs are encouraged to modify the procedures as necessary for specific materials or geometric conditions. However, it is imperative that the procedures in the OEM Structural Repair Manual are followed.

9.5 GENERAL COMPOSITE REPAIR PROCEDURE.

9.5.1 Area Preparation.

Determine the number of plies that have been damaged and the number of extra repair plies, if any, required by the individual repair. If none are specified then the one extra ply is automatically required.

9.5.2 Aerodynamic Surfaces and Solid Laminates.

Taper sand a uniform taper around the cleaned-up damage using a No. 80 sandpaper. The taper is to be over an approximate distance of 0.5 or 1.0 inch for each existing ply depending upon the repair system being utilized. As an option on honeycomb structure, step sanding may be used in place of taper sanding. Caution: Do not count the extra ply when calculating the ply numbers; you could sand too deep.

Remove exterior finish, including enamel finish and conductive coating, from the remaining surface within the masked area using No. 150 sandpaper. Paint stripper will damage the resin system and must not be used.

9.5.3 Interior Surfaces and Noncritical Surfaces.

The taper sanding procedure as outlined in the prior paragraph may be utilized or, when allowable, an external patch may be applied.

Face panels containing two or three plies may be repaired with external, nontapered patches. The damaged area is flush with the original surface using filler plies during the repair lay-up. The repair plies are then installed directly on the resulting smooth surface of the filled area.

Warning: The sanding of structures containing graphite, fiberglass, or Kevlar fibers produces a fine dust that may cause skin irritations. Breathing an excessive amount of the dust may be injurious to your health. Proper personnel protective equipment (PPE) should be employed. The use of a vacuum during sanding will help minimize airborne particulates.

9.5.4 Fabricate Core Replacement.

For butt splicing, the honeycomb core plug should fit flush with the original core and with the ribbon direction the SAME as in the original core. The replacement core must overlap and make intimate contact with the cell walls of surrounding core materials.

For crush splicing, the honeycomb core plug should be made one to three cells (0.38 inch maximum) larger then repair cavity. Trim core plug to full or partial depth of the original core. A schematic of the process is shown in figure 56.

Note: When applicable, an excess of 1/16 inch in core thickness is added to allow for shrinkage during cure and for thickness of extra plies of fabric cloth and adhesive between core plug and undamaged core or skin.

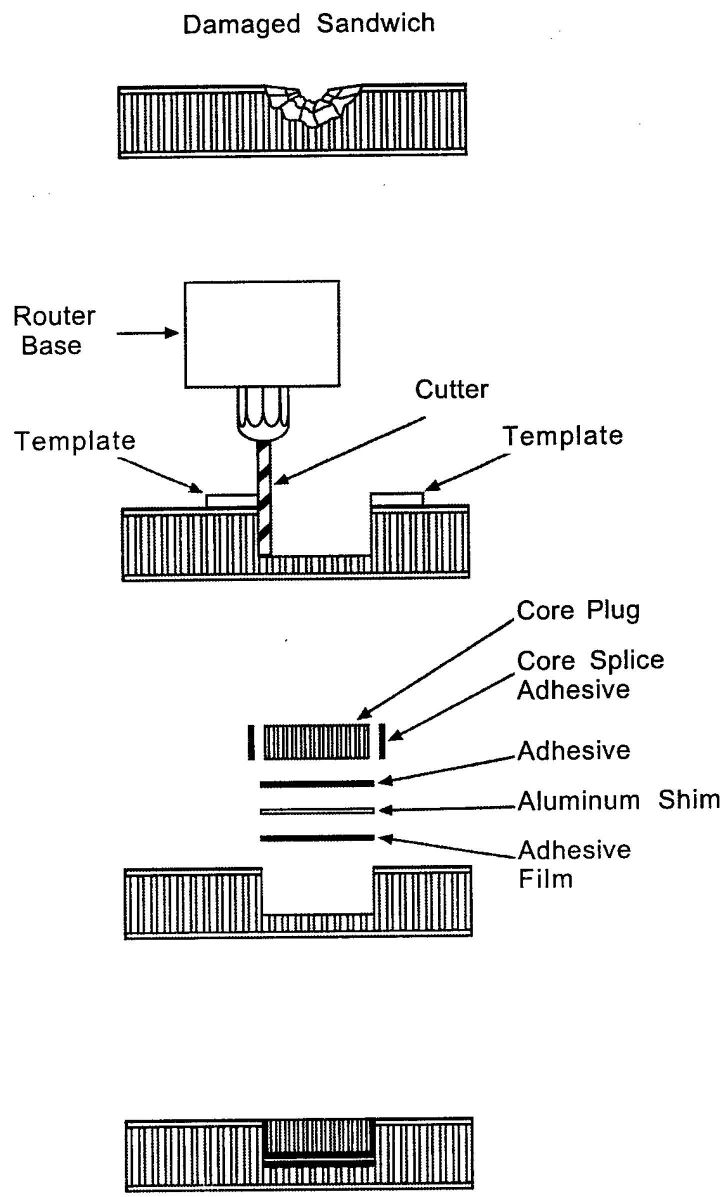


FIGURE 56. REPAIR OF SANDWICH CORE

9.5.5 Clean Core Plug.

Clean visible contaminates from the core by dipping it (a maximum of four times) in an acetone or MIBK or MEK bath for 60 seconds, or vapor degrease the core, limiting immersion to 30 seconds per cycle for a maximum of four cycles. Logically contaminated areas can be washed with acetone or MEK. The core must be completely dry, clean, and free of evidence of solvents before installation.

Warning: Breathing vapors or allowing solvent to contact skin or eyes is hazardous. Heat, fire, or sparks can cause an explosion. Use mechanical ventilation or respiratory protection when

working in a confined space or area. Avoid contact with skin, eyes, and clothing. Wear eye protection. Keep solvent away from sources of heat, sparks, or fire.

9.5.6 Honeycomb Core Cure.

- After cutting and prefitting the core, remove it and clean the bonding surface with MEK or acetone and clean cheesecloth. Allow the solvent to evaporate.

- Insert the core into the core cavity together with the appropriate adhesives.

- Place the lay-up materials and equipment in place.

- Evacuate the repair area to a minimum of 22 inches of mercury and cure.

- After curing the assembly, sand the repair core flush with the surrounding material and vacuum the sanding residue from the core cells.

Note: The above procedure is based on the core plug being cured separately from the repair plies. As an option the core plug installation and repair plies may be cured at the same time.

9.5.7 Cut Replacement Plies.

The repair plies, including the extra plies, should be cut from the same type of fabric with the correct ply orientation as specified on the original engineering plans. The first ply must be either 1 or 2 inches larger in all dimension than the damaged area. Each succeeding ply including any extra plies must be equally larger than the preceding ply.

Note: When replacing plies over a core, an additional ply the size of the damaged area, called a filler ply, is required to minimize surface depression on flush patches.

Filler plies equal to the number of original plies are required for preventing a depression on protruding patches.

Place the repair plies in accordance with the ply orientation and sequence of the base material. The smallest ply should be placed over the repair area first.

9.5.8 Preparation for Cure.

- Place a layer of perforated fluorinated ethylene propylene (FEP) parting film over the repair. Cut the FEP so that the edges extend 3 inches beyond the edge of the repair patch.

- Secure three thermocouples (spaced evenly around the repair) to the panel at the edge of the repair and secure them to the appropriate recorders.

- Place a layer of dry peel ply or style 120 glass fabric (or equivalent thickness glass fabric) over the perforated FEP as a surface bleeder. Cut the surface bleeder so that the edges extend 2 inches beyond the edge of the perforated FEP.

- Place a layer of solid FEP parting film over the surface bleeder. Cut the solid FEP parting film over the surface bleeder. Cut the solid FEP so that the edges are even with the edge of the perforated FEP.

- Place a heat blanket over the parting film. The heat blanket must extend a minimum of 2 inches beyond the repair patch edges. Note: When using a heating blanket larger than 12 inches on one side, an aluminum caul plate (0.016-inch thick) can be used under the heat blanket to minimize localized heating. Make the caul plate slightly smaller than the surface breather. Note: Repairs can also be done using an oven or autoclave press.

- Place controlling thermocouple over the center of the heat blanket.

- Place four to six layers of glass fabric over the heat blanket. The glass fabric will insulate the heat blanket, prevent damage to the bagging film, and act as a breather.

- Apply extruded sealing compound around the entire repair area, approximately 6 inches outside the edge of the heat blanket.

9.5.9 Cure Vacuum Requirements.

Lay vacuum line over the edge of the breather cloth. Stretch a piece of vacuum bag material over the entire repair area. Seal edge with sealing compound. It is optional to envelope bag the entire part. Evacuate to a minimum of 22 inches of mercury. Caution: In the oven or autoclave repair methods, the whole panel must be vacuum bagged to prevent delamination of sandwich skins; contoured parts must be restrained to drawing configurations during hot bond repairing. Bagging to the production tool is preferred. Other shop-made restraining methods are acceptable. The whole process is illustrated in figure 57.

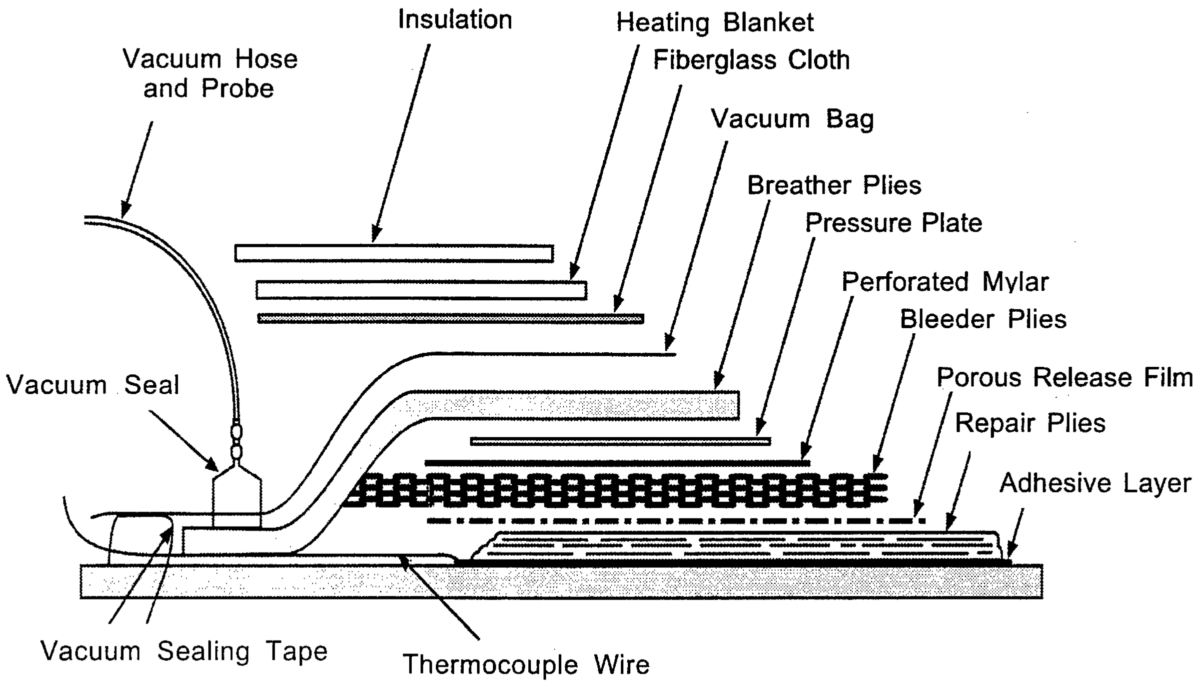


FIGURE 57. TYPICAL BAGGING SEQUENCE

9.5.10 Cure.

Cure by heating at a specified heat based on the lagging thermocouple. Hold for the time specified for cure system used.

9.5.11 Refinishing/Preparation.

Remove all bagging material and lightly sand the surface and the edges of the top ply with 150-grit or finer abrasive to produce a feather edge.

Caution: The use of chemical paint stripper is prohibited because it will attack the composite resin system.

9.5.12 Finishing.

Finish surface repair per applicable method.

9.5.13 Completed Repairs.

Two typical patch repairs are shown in figures 58 and 59 for repairs of plain and sandwich structures. Once the repairs are completed, they have to be inspected and approved by the FAA or its representative before the part is returned to flight status.

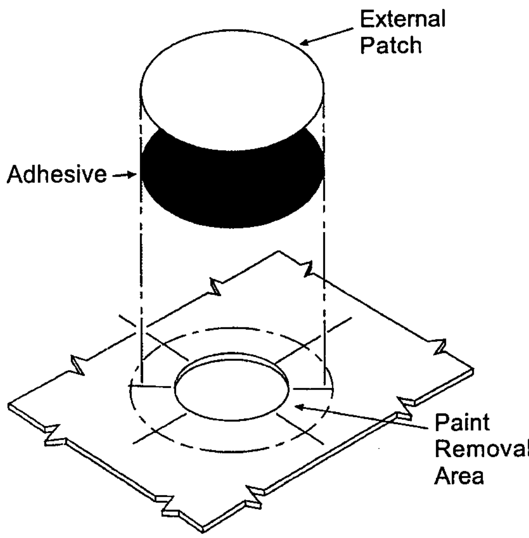


FIGURE 58. TYPICAL PATCH REPAIR

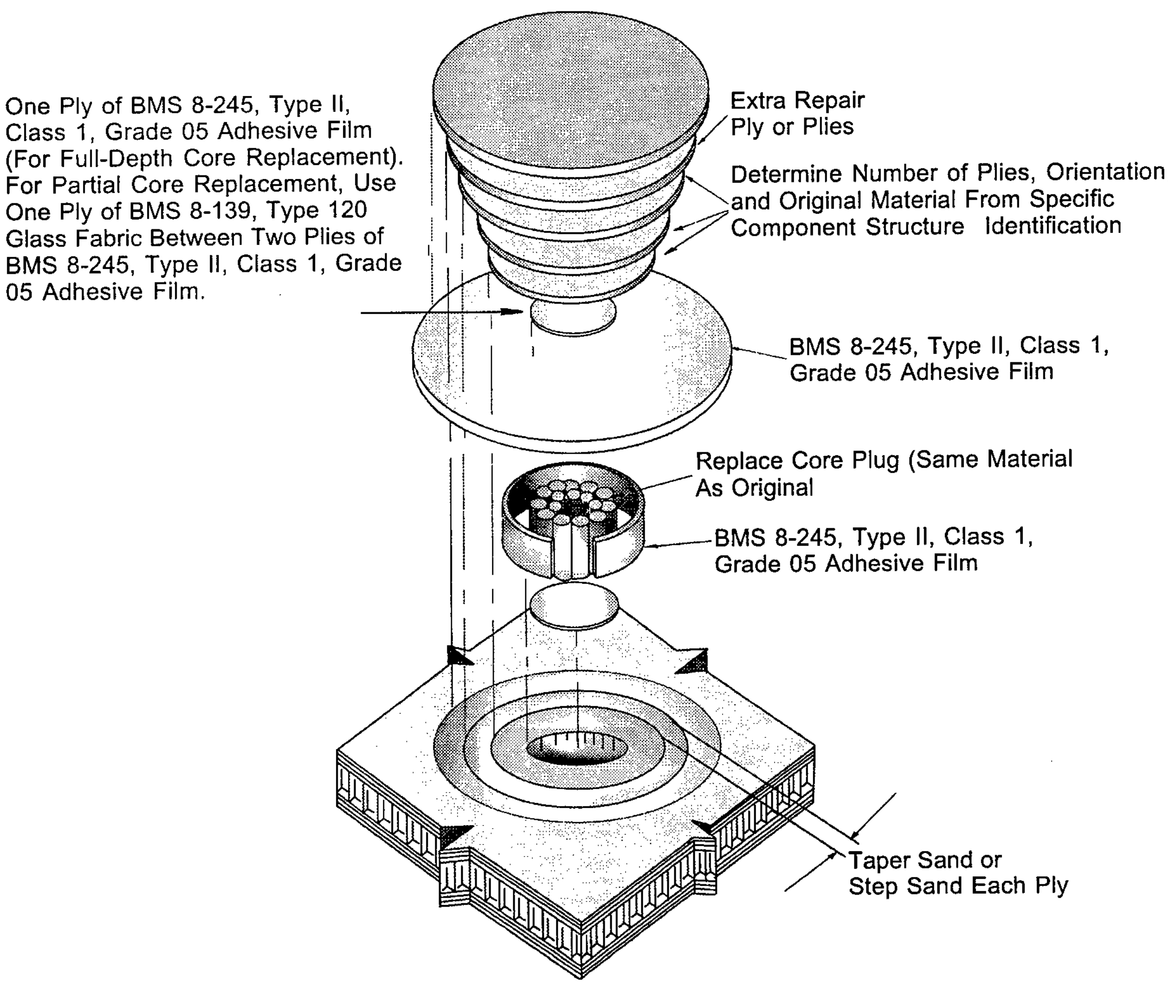


FIGURE 59. TYPICAL SANDWICH PANEL REPAIR

10. ASSEMBLY.

10.1 INTRODUCTION.

Composites, like other structural materials, must be joined and machined to create useful structures. The manner in which these processes are performed is a determining factor in the efficiency and suitability of such components.

There are two basic methods of joining fabricated composite parts. The most common is to use mechanical fasteners such as bolts. They can also be joined together by secondary adhesive bonding or a combination of mechanical fasteners and adhesive bonding. Most joining techniques are considered in the engineering design so that the loads are transferred from one assembly to another efficiently. Joining techniques using mechanical fasteners present unique problems for composite materials. Rates and speeds of drilling or machining may damage the composite material. A caution in joining sandwich parts (composite or metal) may be that they cannot withstand the pullup effect of conventional rivets or bolts. It is necessary to provide a reinforced surface area for bolts with larger nut plates. An example is when skin materials are applied to a core and then subsequently a bolt hole is opened in the skin and through a core. It is necessary to provide solid materials under the bolt hole such as densifying or potting compounds. This prevents crushing the core cells by virtue of the mechanical force exerted by tightening up the bolt.

10.2 MECHANICAL FASTENING OF COMPOSITES.

Mechanical fastening of laminated composites is an effective joining technique when consideration is given to the following:

- tensile and bending stresses in the fastener
- strength and flexibility of the fastener
- loss of tensile/compressive strength capability in the laminate due to the hole
- shear distribution in the joint
- clearance between fastener and joining members
- friction between parts
- allowable bearing stresses
- types of fasteners
- fatigue requirements

Composites are mechanically fastened in a manner similar to metals; for example, joining members are drilled and countersunk and joined with rivets, bolts, screws, or pins. However, because composites have low through-the-thickness strength and are less malleable, special methods of joining and unique fasteners have been developed for use with composites. The joining method is based on consideration of component required strength (static and fatigue), reliability, ease of fabrication, cost, and special joint criteria (removable, replaceable, etc.).

10.2.1 Fastener Selection.

The use of mechanical fasteners to join nonmetallic composite structures is bound by certain constraints which do not exist in the design of metallic joints. In other words, special care must be taken to select fasteners that are appropriate with polymer composite structures. Because of these special requirements, fastener manufacturers have developed fasteners especially for use with composites. This has resulted in an increase in the bearing area of fastener heads (or tails) in order to reduce the axial stresses against the laminate when the fastener is loaded in tension. These fasteners develop the full bearing capability of the composite (which, at least for carbon/epoxy, is equal or better than aluminum) without encountering local failure modes (pullthrough) and are not susceptible to corrosion. Therefore, these fasteners or those having such properties should be used. Nondiscriminant use of off-the-shelf fasteners will lead to premature joint failures.

Another problem is the composite's inability to support installation stresses of formed fasteners such as solid rivets or blind fasteners with bulbed tails. In addition to surface damage such as digging into the composite, subsurface damage to the laminate may occur. For this reason, these fastener types are avoided in favor of two piece fasteners and blind fasteners which do not generate this type of loading during installation.

For the above reasons, tension head 100° countersunk fasteners rather than shear heads are used as the projected area of the tension head fastener is larger than that of a shear head fastener. The larger area improves pull-through and delamination resistance in composites, while reducing overturning forces from bolt bending. These fasteners are also recommended for double shear joints. Caution should be observed in the use of 130° countersunk head fasteners. Although this type of fastener increases the bearing area of the fastener and permits it to be used in those laminates, pull-through strength and resistance to prying moments can be adversely affected.

The full bearing capability of composites can only be attained using fasteners with the high fixity (good clamp up). Fixity is a function of fastener stiffness, fastener fit, installation forces, torque, and rotational resistance of the fastener head and collar or formed backside. However, overtorquing can result in composite damage.

The most obvious method for preventing a high stress assembly is to carefully control the tightening of all fasteners with properly adjusted torque limiting drivers. This can work fine when operations are confined to a factory assembly line, but field or customer assembly presents a difficult control problem. Even when torque can be controlled, sometimes a poorly designed bolted assembly will result in an assembly torque which is too low for proper installation. In this case, design modifications will be required.

Although close tolerance fit fasteners are desirable for use with composites, interference fit fasteners cannot be used due to potential delamination of plies at the fastener hole. There are

exceptions to this rule. Some automatic high-impact driving equipment which was used in production has been shown not to cause composite damage.

Presence of galvanic corrosion between metallic fasteners and nonmetallic composite laminates has eliminated several commonly used alloys from consideration. Conventional plating materials are also not being used because of compatibility problems. The choice of fastener materials for composite joints has been limited to those alloys which do not produce galvanic reaction. The materials currently used in design include unplated alloys of titanium and certain corrosion resistant stainless steels (cres) with aluminum being eliminated. The choice is obviously governed by the makeup of the composite materials being joined, as well as weight, cost, and operational environment. Aircraft maintenance practice has been to coat fasteners with the anticorrosion agent to further alleviate galvanic corrosion.

Equipment required to install fasteners ranges from simple hand tools to sophisticated automated machinery. Typical methods include bolted assemblies, self tapping screws, rivets, threaded inserts, spring clips, and any other mechanical devices which join parts together. The key advantages of these mechanical fasteners are that they are readily available, easy to use, do not require complex tooling or special preparation, and most allow for simple nondestructive disassembly. Disadvantages are that extra parts must be stocked, and care must be taken to prevent the assembled parts from becoming overstressed. Also, creep can result in loss of preload if systems are poorly designed.

10.2.2 Joint Design.

The primary considerations of composite joint designs are bearing, shear tearout, tensile/compressive strengths in the composite, and shear/bending stresses in the fastener. Additional factors of concern are thermal stresses, fatigue requirements, and the operational environment.

Net tension/compression and shear-out strengths are a strong function of laminate configuration, joint geometry, and hole size, but they are only marginally dependent on fastener type, joint configuration, or environment. The shear-out mode of failure is usually avoided in design by providing sufficient edge distance between the holes or the free edge and balanced laminate configuration. However, in certain rework situations shear-out critical joints cannot be avoided. Larger edge distances than for metals (width to fastener diameter ratio equal or greater then six) are used in composites to prevent net-tension/compression failures. On the other hand bearing and fastener pull-through strengths are greatly influenced by the type of fastener used and its clamp effects, bolt stiffness, head and tail areas, countersinking, etc. The laminate lay-up and stacking sequence do not affect bearing or pull-through strengths significantly unless extreme lay-ups are used. The extreme being defined as a laminate having highly concentrated plies or plies in only two directions.

Several types of mechanical joints have been successfully used in composites: laps, butt plate (single and double shear), tapered butt plate, offset lap, and others. In the double-shear butt joints, the bending stresses common to the other joints are avoided while the tapered butt-plate joint minimizes excessive loads at the first bolt of the joint.

10.3 ADHESIVE BONDING.

The adhesives most used in bonding composites are polymeric materials which are similar in many ways to the matrices of the composites themselves. Just as epoxies are the most common matrix for advanced composites, epoxy adhesives are also the most common. Epoxy adhesives can be either one stage (curing agent already mixed in) or two stage where the user mixes in the curing agent just before use. The form of the one-stage material is often a sheet, very much like a prepreg without the reinforcement, or a paste. The two-stage system must be a paste or thick liquid. Less viscous materials have proven to be difficult to control in precise placement.

Proper adhesive application is as important as proper bond design and adhesive choice to obtain maximum joint properties. Improper adhesive application techniques can result in partial or complete failure of an assembly. Care should be taken not to incorporate air into the adhesive during application. Entrapped air can expand during cure to give porous and weakened bonds. The use of scrim cloths are a must to insure minimum bond thickness and eradicate starved areas. Care should be taken to avoid contaminating adhesive and cleaned assemblies. Contamination could result in hindered wetting action and cause inferior results. Solvents used to clean excess bonding material must be used in a manner as not to come in direct contact with bond area. All adhesives are sensitive to the surface conditions of the materials to be joined.

Both room temperature and elevated temperature curing systems are utilized. In many cases, the room temperature curing adhesives require postcuring to develop good mechanical properties at elevated temperatures. Cure times can range from a few minutes, for simple noncritical parts, to more than 12 hours for large, critical-performance parts.

Epoxy adhesives have good bond strength and environmental resistance. Epoxies generally have poor peel strength, thus they are sometimes modified with rubber materials to improve peel strength characteristics. However, rubber toughening also increases the sensitivity to moisture and creep.

In applications where peel strength is very important and an adhesive joint is preferred over mechanical, rubber-based adhesives are used. These adhesives can be used on butadiene (conventional rubber), polyurethane, silicone, and polysulfides, to name a few. All of these materials have higher peel strength and lower shear strength compared to the epoxy adhesives. Conventional rubber-based materials are the least expensive, but the others can be chosen for special applications such as solvent and oxidation resistance, high temperatures, moisture resistance, or a combination of properties. High molecular weight additives, usually elastomers, give additional flexibility in the formulation if they are added.

Thermoplastic materials (which are solids at room temperature) are also used as adhesives for composites. These materials are called hot-melt adhesives since they are melted to become fluid so they can be applied to the materials to be joined and then they harden when cooled. Hot melts are most often used when speed in bonding is important. They should be avoided in applications where creep would be a problem.

10.4 PART PREPARATION.

All parts are cleaned and primed before assembly or adhesive bonding processes.

10.4.1 Vapor Degreasing.

This process removes organic soil and contamination from metal or composite parts. Perchloroethylene is heated to 180 to 195°F causing the solvent to vaporize in a tank/condenser. Parts are then placed in this vapor.

This process requires that parts shall be free of water when placed in the degreaser. Usually the parts are lowered into the vapor zone, using a hook, crane, basket, or other suitable means. Parts then remain in the degreaser until liquid condensation can no longer be seen dripping (usually 1 minute for small parts and 5 minutes for large parts). As the solvent vapor is harmful, avoid skin contact and use adequate ventilation.

10.4.2 Primed Parts.

No uniform or standard method has been developed for painting or coating composite materials. However, a thorough cleaning of the surface is fundamental to any method that might be used. One surface preparation sequence would include the following:

- Sand or abrade
- Solvent wipe
- Apply fillers
- Sand or abrade the filled areas.
- Solvent wipe (may include cleaning with water and detergent as well)
- Apply primer sealer
- Paint

The use of peel plies with specific roughness characteristics have simplified this cleaning and abrading procedure to eliminate all but the last solvent wipe and then priming and painting. Paints and primers should dry/cure at temperatures below the cure temperature of the part.

After the priming process is complete, parts are wrapped and sealed in plastic film and prepared for bonding as follows:

- Dry wipe with clean cheese cloth
- Alcohol wipe
- Air dry 10 minutes prior to applying adhesive.

10.4.3 Metal Preparation for Bonding.

Adhesive bonding is increasingly gaining acceptance as a method of fastening details into an assembly. The use of load-bearing adhesives was pioneered by the aircraft industry because of the advantages bonded joints have over other methods of fastening. Metal-to-metal adhesives are chiefly used in thin metal lap joints in place of rivets, spot welds, and other mechanical fastening methods. In addition, structural adhesives are used extensively for joining metal skins to honeycomb core in the manufacture of sandwich panels.

Like any other structural material, adhesives have their limitations and optimum service environment. The success of this process relies heavily on the preparation methods used prior to any adhesive application and subsequent processing. In addition to the traditional abrasion preparation techniques, there are two other processes of surface preparation commonly used in the aircraft industry.

- Chromic Acid Anodize Process—This surface treatment is a system whereby the substrates (typically aluminum) are chemically treated to create an oxide surface on that alloy. This surface treatment is a transformation process, changing the aluminum surface with unknown and perhaps undesirable properties to an oxide surface with known desirable properties. Aluminum is basically treated electrolytically in a dilute solution of chromic acid to produce a coating that effectively prevents corrosion. Corrosion-inhibiting primers such as zinc chromate are then applied immediately afterwards to provide further corrosion resistance. This process has been used as far back as World War II with reliable results.

- Phosphoric Acid Anodize Process—As an anodizing process, this method provides an open, porous, oxide surface that is different from any other common method of anodizing such as chromic acid and sulfuric acid. The major differences are that this oxide provides much larger pores and is much thinner and will not hydrate or seal as well as the chromic acid method. However, this process does provide excellent adhesion of organic coatings and adhesives. It is the combination of this process and the subsequent application of an organic coating (primer) that provides the superior corrosion protection and environmental durability. This process basically provides a porous surface to the substrate through a series of applications of voltage and chemical solutions. This process also requires the immediate application of a corrosion inhibiting primer.

- Other Preparation Processes—Local treatments can be utilized for preparation when anodizing or etching is not applicable. Surface abrasion and/or subsequent application of any one of a variety of chemicals; i.e., methyl ethyl ketone (MEK), trichlorethylene (TCE) isopropyl alcohol, and hand applied acids such as sulfuric-dichromate (FPL etch), hydrofluoric acid, and Pasajell 105 are all acceptable methods for optimization.

After surface treatments and bonding operations are complete, destructive and nondestructive testing methods of proving the quality of adhesive bonded joints and the preparation should be used.

10.5 ASSEMBLY PROCEDURES.

The manufacture of composite aircraft parts involves fabrication level work such as ply cutting and autoclave processing as well as assembly level work, drilling, and attachment of fittings. Assembly of composite aircraft structures is often performed in several stages. Normally, any operation performed on a composite part after cure is considered an assembly operation.

Because of the unique tooling required for composite drilling and trimming, the assembly tools have special requirements. Any location on the composite part that requires drilling will require bushings on the assembly tool that are designed to accept the make of the drill motor to be used. The drill motors have automatic feeds and require that they be attached to a stabilizing drill fixture to maintain drill alignment. The locating of parts in the assembly tool is accomplished in a manner similar to that in a metallic assembly. Combinations of locating tabs, tooling holes, templates, and other aids are used to properly locate the assembly. Numerous locators are required to position all the ribs and spars. Prefit of detail parts, which determine the final fit-up accuracy, is considered part of the assembly operation.

Fit-up of parts during assembly is of utmost importance in composites irrespective of whether the parts are to be joined using mechanical fasteners or adhesive. Structural or nonstructural shimming is used depending on the size of the gap. (For load-bearing parts, 0.03 in. thickness is the dividing line between structural and nonstructural shimming in airframe construction.) If a gap is left between the skin and the substructure in the vicinity of fastener hole, the fastener will not have proper bearing support. When the fastener is torqued up, the transverse load closes the unshimmed gap and may create a multilevel delamination in the skin, the substructure, or both, depending on the relative strength and stiffness of the elements.

A combination of other factors, illustrated in figure 60, can contribute to composite structural delaminations at fasteners. For example, assembly induced delaminations can take place when a geometric mismatch exists between the fastener and the hole. Such a mismatch may be caused by a tilted fastener, an O-ring seal groove, or a hole machined with a dull countersink tool. In all these cases, the stress concentration induced by the geometric mismatch often results in premature failure of the laminate during fastener torque up. If improper shimming procedures are

observed during assembly, postassembly NDI inspection should be performed to determine if any damage exists in the structure.

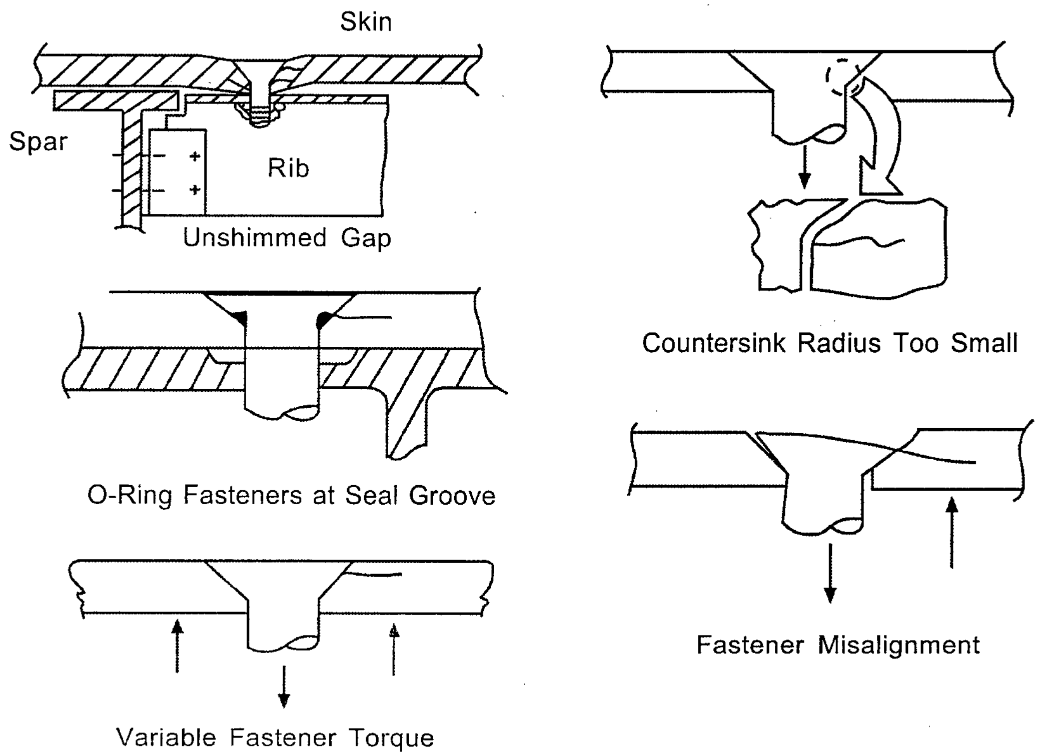


FIGURE 60. A COMBINATION OF FACTORS MAY CAUSE DELAMINATIONS AT FASTENER HOLES

11. SAFETY, HEALTH, AND ENVIRONMENT.

11.1 INTRODUCTION.

The following are recognized hazards associated with advanced composite materials. By knowing these hazards, you can prevent adverse exposure to them. It is important that the technician read and understand the Material Safety Data Sheets (MSDS) and handle all chemicals properly.

11.2 MATERIAL SAFETY DATA SHEETS AND WARNING LABELS.

Each material has its own physical, chemical, and toxic properties. To work safely with the material, the technician will need to know these properties. The MSDS provides health and physical hazard information about a particular chemical or material. Information regarding safe handling procedures, recommended personal protective equipment (PPE), and first aid measures are also included. An MSDS must be available for each hazardous material used at a location.

A product warning label also provides important hazard information and should be located on each hazardous material container. Warnings, such as flammable or corrosive, on the label are meant to prevent improper use or careless handling.

11.3 PERSONAL PROTECTIVE EQUIPMENT.

Personal protective equipment (PPE), figure 61, is used to prevent exposure to hazards that cannot be controlled in other ways. When working with advanced composite materials, PPE is used to protect the skin, eyes, mouth, throat, and lungs.

FIGURE 61. PERSONAL PROTECTIVE EQUIPMENT (PPE)

Gloves are very important for protecting skin when touching chemicals. Gloves must be the right type in order to protect the skin from the chemical being used. Certain tasks or procedures may require gloves that protect from heat or cuts, but they may not offer protection against chemicals. In those cases, more than one type of glove may need to be worn at the same time and in a certain order to protect the technician.

Other protective clothing, such as aprons, lab jackets, and coveralls, may be needed for certain operations. The technician must make sure to use all the protective clothing needed for the task or operation.

Eye protection is available in many forms, but the three basic types used are safety glasses, goggles, and face shields. The technicians eyes need to be protected from chemical splashes, dusts from machining, and flying particles. The technician must have impact resistant eye protection. Safety glasses and goggles protect against impact. Only goggles with indirect ventilation can protect against chemical splashes. A face shield needs to be used with other eye protection.

Respirators may be used to keep the technician from breathing dusts, fibers, or chemical vapors during resin mixing, lay-up, curing, machining, or clean-up operations. The most common respirator used in composites work is the air-purifying respirator. It filters contaminants from the air breathed. It is very important to use the proper filtering material. A respirator does not protect the user if it is the wrong type, if the filter is dirty, or if it does not fit correctly.

11.4 RESINS.

The primary danger with uncured resins is that they can irritate the skin and eyes. If you touch these resins, your skin may turn red or swell. This condition is called dermatitis. If it is not treated, dermatitis may progress to more serious skin problems.

Some people are allergic to certain resins and their skin erupts after very little exposure. This is called skin sensitization and results from repeated contact with the same material. Contact with chemicals through the skin may result in some chemicals being absorbed through the skin into the body and may cause damage to body organs such as the liver or kidney. Certain resins, especially when heated, may produce vapors that can irritate the eyes, respiratory tract, and skin.

11.5 CURING AGENTS.

Curing agents, also called hardeners or catalysists, are used to cause a faster chemical reaction in thermoset resins. These materials are often skin and eye irritants and some may cause skin sensitization. Certain curing agents cause damage to the liver and other vital organs.

11.6 FIBER REINFORCEMENTS.

Fiber reinforcements give strength to the finished part. Irritation can result from the rubbing action of fibers on the skin. The irritation can be increased by contact with chemicals.

Common places for fiber irritation are the neck and waist when clothing is tight fitting. Technicians or operators may also feel irritation of the eyes and nose when working with these fibers. Most fibers are too large to get into the lungs, but pieces of fiber from cutting or machining may be small enough to reach the lungs in normal breathing. These are called respirable fibers. Breathing a lot of these fiber pieces over extended periods of time may cause lung damage.

11.7 DUST.

Machining and finishing cured composite parts or cutting uncured prepreg may generate a lot of dust. This dust may be harmful. Very fine dust may be taken into the lungs, so protective masks (or respirators) should be worn. If ventilation cannot remove the dust, machining of cured parts can result in flying particles which can injure the eyes or skin.

When working with composites and bonding films, dust and fumes are given off by various operations. Dust and/or decomposition of products is created by sawing and surface grinding. Power trimming or otherwise abrading of cured composite materials is considered a health hazard.

Decomposition of composites occurs during trimming. Because of friction generated by high-speed cutting, various materials are burned away which creates toxic fumes. Toxicity will vary for different types of composites and bonding films; therefore, one must consider all equally hazardous and observe safety guidelines. These are:

- Always work on down draft tables.
- Wear proper dust respirator.
- Always wear safety glasses.
- Wear ear protection when working in trim booths.
- Never wear loose clothing (because of vacuum table suction).
- After trimming operation, remove dust from parts on downdraft table only.
- After trimming, wash hands before eating or smoking.

11.8 SOLVENTS.

Many different solvents are used with advanced composite materials and each has its own hazards. Solvents are mixed with resins to make them easier to process and many are flammable.

Breathing solvent vapors may cause nose and throat irritation, dizziness, headaches, or drowsiness. If very high concentrations of solvent vapors are inhaled, you may lose consciousness and die.

Solvent contact will dry the skin and may result in dermatitis. Some solvents are absorbed directly through the skin and may carry other chemicals with them, possibly causing liver or other organ damage.

11.9 INERT GASES.

Carbon dioxide and nitrogen are commonly used in composite material operations. Solid carbon dioxide (dry ice) is used as a packaging material to keep prepregs cold to maintain their shelf life. Liquid nitrogen and liquid carbon dioxide are used for cold testing of composite materials. Nitrogen gas is used in autoclaves during cure to keep parts from burning.

Either carbon dioxide or nitrogen gas may cause immediate unconsciousness and suffocation in low-oxygen atmospheres. Dry ice or liquid gas also pose a frostbite hazard upon contact with skin or eyes.

11.10 MIXING, MOLDING, OR CURING OPERATIONS.

Resin mixing, part molding, or curing operations may release vapors that irritate the eyes, nose, and throat. Severe burns can result from touching the hot material or equipment.

During resin processing, it is possible to have a resin rapidly heat and react in an out-of-control chemical reaction, called an exotherm (giving off heat). During the exothermic process, the temperature rises quickly and large amounts of smoke are released. Breathing the smoke may cause eye, nose, and throat irritation, nausea, dizziness, and headache. Severe burns could occur if hot resin touches the skin.

11.11 VENTILATION.

Ventilation is a good means of keeping concentrations of air contaminants, such as vapors or dust, as low as possible. There are two basic types of ventilation, general and local. General ventilation is the fresh air exchange for a room, an area, or an entire facility. Local ventilation is usually for a small area or one machine. Local ventilation is typically a hose or vent designed to draw dust, vapors, or other air contaminants away from a work area or operation. Well designed general or local ventilation can reduce exposures to solvent vapors, fibers, and dust from machining and finishing operations.

11.12 PERSONAL HYGIENE.

Keeping clean is an important form of controlling exposures to dusts, chemicals, and fibers. Washing hands with soap and water and using moisturizing creams will help keep the skin healthy. Regular bathing, with clean cloths, can help prevent contact with irritating materials. The technician should not smoke, eat, drink, or store food in areas where chemicals are present. It is easy to accidentally get chemicals into the body if the technicians do not follow these guidelines.

11.13 FIRST AID.

Proper first aid is important no matter how minor an incident seems to be. If not treated, minor cuts or irritants could turn into serious situations. Chemicals could enter the body and minor irritants could turn into dermatitis or worse if not treated immediately. No incident is too minor to report.

11.14 HOUSEKEEPING.

The technician's work area should be kept clean to prevent contamination to both the product being manufactured and the technician in the workplace. Spills of any type should be cleaned up immediately to avoid safety and health hazards as well as prevent a more difficult clean up later.

A vacuum cleaner should be used to remove dust and fibers. Compressed air should not be used for this, as it throws the dust in the air and can blow particles into the eyes of a coworker. Also, blowing dust and dirt creates an even bigger housekeeping problem.

11.15 SAFETY CONTROLS.

The following operations are especially hazardous and require special precautions.

- Working in a confined space where hazardous chemicals or vapors may be present.
- Working with open flames or spark-producing equipment in areas that may contain flammable vapors or gasses.
- Working on equipment with guards or other protective devices removed.

Individual companies should have standard operation procedures for each of these examples.

11.16 WASTE DISPOSAL.

Advanced composite materials are being produced, transported, stored, used, and disposed of every day. Everyone using these materials must understand how they effect human health and the environment, both now and in the future.

Each manufacturer and fabricator must do as much reduction of waste at the source, reuse, and recycling as possible. Lastly, if disposal is necessary, proper disposal under federal, state, and local laws needs to be followed.

11.17 PERSONNEL QUALIFICATIONS.

Personnel must be fully qualified to work with advanced composite materials and adhesives that are used in commercial aerospace programs. The following procedure outline provides insight to

environmental, housekeeping, and personal protective or preventive suggestions. Some of these details can be found on typical manufacturing work sheets issued for part fabrication and assembly.

11.18 WORK ENVIRONMENT.

The area where surface cleaning of the details is to be accomplished should be isolated from operations that generate dust, oil, vapors, or other contaminants. All personnel handling cleaning details shall wear clean, white, lint free cotton gloves. Immediately after cleaning, details shall be moved into a controlled atmosphere area. Operations that generate dust or other airborne contaminants should not be permitted in the controlled area, and activities such as sanding or grinding are forbidden. Similarly, smoking or eating is also forbidden.

11.19 GOOD HOUSEKEEPING.

Some typical housekeeping rules are:

- Each employee is responsible for his/her own immediate work area and shall immediately clean up when assigned to another job or at end of shift.
- When components are removed from tools, all parts of the tool will be immediately cleaned and installed back in proper position and the tool moved to the appropriate storage or preparation area.
- Trash cans in one's own immediate work area will be emptied at the end of each shift.
- Tools or supplies put in cabinets will be stored neatly.

No lunches, food, or beverages will be permitted on work benches. They must be stored under the work bench. (Note: none of the above are permitted in the clean room.)

11.20 TOOLS.

As tool integrity is critical for obtaining good parts, special care must be observed such as:

- All tools (bonding fixtures, trim bonnets, drill plates, etc.) are to be checked for current inspection dates prior to use. Any outdated tool will be referred to supervision.
- Tools should be used only for the intended purpose.
- Tools will be kept clean and stored properly and maintained in good condition.
- Damaged tools will be referred to supervision for manufacturing engineering action.

11.21 MISCELLANEOUS.

Some special rules of handling composites are:

- Prepreg materials and adhesives will be checked for identification and expiration date prior to use. Any outdated material will be brought to the attention of inspection or supervision for proper disposition.

- Panels will be protected from damage by using cardboard separators or rubber matting.

- Sharp metal instruments should not be used to clean excess squeeze-out of panels.

- Good workmanship habits should be developed and practiced to produce a quality product.

- Wear a face shield or safety glasses while using machining equipment.

After the cure cycle is complete and the assemblies are debagged and unloaded, a number of them will be diverted to a protective application area where gum-backed paper may be applied.

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13. GLOSSARY.

Absorption. Penetration of one substance into the mass of another.

Accelerator. Accelerators are added to an epoxy resin-curing agent mixture to speed up a sluggish reaction.

Aging. Effect on materials of exposure to an environment after a time interval.

Air bubble void. Entrapment of air between plies or in a bond line.

Ambient. Surrounding environmental conditions, such as pressure, temperature, or relative humidity.

Angle-ply laminate. A laminate with fibers of adjacent plies oriented at alternating angles.

Antistatic agents. Agents that when added to a molding material or applied to a surface make the material less conducting, hindering the attraction of dust or build-up of electrical charge.

Areal weight. Weight of fiber per unit area (width x length) of tape or fabric.

Autoclave. Pressure vessel in which assemblies are placed for curing when even pressure and temperature are required.

B-stage. An intermediate stage in the reaction of a thermosetting resin in which the material softens when heated and swells when in contact with certain liquids but does not entirely fuse or dissolve. Materials are usually precured to this stage to facilitate handling and processing prior to final cure. (Sometimes referred to as resitol.)

Bag molding. Technique to produce molded parts by fluid pressure through a flexible membrane.

Bagging. Applying an impermeable layer of film over an uncured part and sealing edges so a vacuum can be drawn.

Barrier film. Layer of film used to permit removal of air and volatiles from a composite lay-up during cure with minimal resin loss.

Batch (or lot). A quantity of material formed during the same process and having statistically identical characteristics.

Binder. Bonding resin used to hold strands together in a mat or preform during manufacture of a molded object.

Blanket. Material plies that have been laid up in a complete assembly and placed on or in the mold all at one time. Also the form of bag in which the edges are sealed against the mold.

Bleeder cloth. Woven or nonwoven layer of material used in manufacturing composite structures to allow the escape of excess volatiles and resin during the cure cycle. The bleeder cloth is removed after the curing process and is not part of the final part.

Bleeding. Removal of excess resin from a laminate during cure.

Blow-by. Flow or leakage of internal air pressure through the part and out through the vacuum vent lines that exhaust to the atmosphere.

Bond. Adhesion of one surface to another, with or without the use of an adhesive as a bonding agent.

Breather cloth. Loosely woven material that serves as a continuous vacuum path over a part but is not in contact with the resin.

Breathing. Opening and closing of a mold to allow gas to escape early in the molding cycle. Also known as degassing.

Bridging. Condition where one or more plies of prepreg, bag film, breather, release film, tape, fabric, etc., span a radius, chamfered edge of core without full contact.

Bundle. General term for a collection of parallel filaments or fibers.

Carbon fibers. Fibers made from a precursor by oxidation and carbonization and not having a graphitic structure.

Caul plate. Smooth metal plate free of surface defects and the same size and shape as a composite lay-up and used in immediate contact with the lay-up during the curing process to transmit uniform pressure and to provide a smooth surface to the finished part.

Cavity. Depression in a mold, the space inside a mold where resin is poured, the female portion of a mold. Molds are designated as a single cavity or multiple cavity depending on the number of depressions.

Clamping plate. Mold plate fitted to the mold and used to fasten the mold to the machine.

Clamping pressure. In injection molding and in transfer molding, the pressure which is applied to the mold to keep it closed, in opposition to the fluid pressure of the compressed molding material.

Cocuring. The act of curing a composite laminate and simultaneously bonding it to some other prepared surface during the same cure cycle.

Coefficient of thermal expansion. The change in volume per unit volume produced by a 1-degree rise in temperature.

Compaction. The application of a temporary vacuum bag and vacuum to remove trapped air and compact the lay-up.

Composite. A material containing two or more distinctive material (fillers, reinforcing material, and compatible resin) designed to develop specific performance properties.

Contact pressure resins. Liquid resins that thicken on heating, and when used for bonding laminates, require little or no pressure.

Continuous filament. A yarn or strand in which the individual filaments are the same length as the strand.

Coupon. Specimen for a specific test, such as tensile coupon.

Crazing. Apparent fine cracks at or under the surface of an organic matrix.

Crossply. Any filamentary laminate in which the laminae are at right angles to one another.

Cure. To change the properties of a resin by chemical reaction, which may be condensation or addition, usually by either heat or catalyst or both, with or without pressure.

Cure cycle. The cycle of time/temperature/pressure used to cure a thermosetting resin system or prepreg.

Curing agent. Catalytic or reactive agent which, when added to a resin, causes polymerization. Also called hardener.

Curing temperature. Temperature at which a cast, a molded or extruded product, a resin-impregnated reinforcement, or an adhesive, etc., is subject to curing.

Curing time. Length of time a part is subjected to heat, pressure, or both to cure the resin.

Cycle. Complete repeating sequence of operations. In molding, the cycle is the period between a certain point in one cycle and the same point in the next.

Debond. A deliberate separation of a bonded joint or interface, usually for repair rework purposes.

Debulking. Compacting of a prepreg stack under moderate heat, pressure, and/or vacuum to remove most of the air to ensure seating on the tool and to prevent wrinkles.

Deformation. Change in shape of a specimen caused by the application of a load or force.

Delamination. Separation of layers of material in a laminate.

Denier. A numbering system for expressing linear density equal to the mass in grams per 9000 meters of yarn, filament, fiber, or other textile strand.

Density. The mass per unit volume.

Deviation. Variation from a specified dimension or requirement.

Disbond. Area within a bonded interface between two adherends in which an adhesion failure or separation has occurred.

Dry fiber area. Area of fiber not totally encapsulated by resin.

Dry lay-up. Construction of a laminate by layering preimpregnated reinforcement (partly cured resin) in a mold, usually followed by bag molding or autoclave molding.

Ductility. The ability of a material to deform plastically before fracturing.

Dwell. A pause in the application of pressure to mold made just before the mold is completely closed to allow the escape of gas from the molding material. Also can be used for staging temperature to gel point control.

End. A single fiber, strand, roving, or yarn being incorporated or already incorporated into a product.

Elongation. Deformation caused by stretching

Extensometer. A device for measuring strain.

Fabric. A material constructed of interlaced yarns, fibers, or filaments. Nonwovens are sometimes included in this classification.

Fabric fill face. Side of the woven fabric where the greatest number of the yarns are perpendicular to the salvage.

Fabricating, fabrication. Manufacture of plastic products from molded parts, rods, tubes, sheeting, or extrusions by punching, cutting, drilling, and tapping. Fabrication includes fastening plastic parts together or to other parts by mechanical devices, adhesives, heat sealing, or other means.

Felt. A fibrous material made up of interlocked fibers by mechanical or chemical action, moisture, or heat; made from asbestos, cotton, glass, etc.

Fiber. Term used for filament materials.

Fiber content. The amount of fiber present in a composite usually expressed in percent volume.

Fiber direction. Orientation or alignment of the longitudinal axis of the fiber.

Fiber-reinforced plastic (FRP). Term for composite that is reinforced with cloth, mat, strands, or any other fiber form.

Filament. The smallest unit of a fibrous material. Filaments are usually of extreme length and very small diameter.

Filament winding (continuous). An automated process in which continuous filament strands are resin-treated and wound on a removable mandrel in a pattern.

Fill. Yarn running from salvage to salvage at right angles to the wrap in a woven fabric.

Filler. Insert material added to a resin mixture to reduce cost, modify mechanical properties, add color, or improve surface texture.

Filling yarn. Transverse threads or fibers in woven fabrics running perpendicular to warp. Also known as weft.

Fisheye. Small globular mass which has not blended completely into the surrounding material and which show particularly in a transparent or translucent material.

Flash. Extra plastic which has flowed out of the mold cavity along the paring line during molding and must be removed. Also adhesive flash and resin flash in vacuum/autoclave bonding.

Gel. The initial jelly-like solid phase that develops during the formation of a resin from a liquid. A semisolid system consisting of solid aggregates in which liquid is held.

Gel coat. A resin applied to the surface of a mold and gelled prior to lay-up. The gel coat becomes an integral part of the finished laminate and is usually used to improve surface appearance and bonding.

Gel point. The stage at which a liquid begins to exhibit pseudoelastic properties. Also known as gel time.

Graphite fibers. Fibers made from a precursor by oxidation, carbonization, or graphitization process (provide a graphitic structure).

Greige. Fabric that has not received a finish.

Hand lay-up. The process of placing successive plies of reinforcing material of resin-impregnated reinforcement in position, on a mold, by hand.

Hardness. Resistance to surface deformation, usually measured by indentation. Types of standard tests include Brinell, Rockwell, Knoop, Shore, and Vickers.

Heat cleaned. Glass or other fibers which have been exposed to elevated temperatures to remove preliminary sizings or binders which are not compatible with the resin system to be applied.

Heat sealing. Method of joining plastic films by applying heat and pressure simultaneously.

Heterogeneous. Term for a material consisting of dissimilar materials.

Homogeneous. Term for a material of uniform composition throughout.

Hot wet lay-up. A method of fabricating a reinforced product by applying a hot resin system as a liquid when the reinforcement is in place. Hot setting adhesive/resin requires a temperature of 60°C (140°F) to set.

Humidity, relative. The ratio of the pressure of water vapor present to the pressure of saturated water vapor at the same temperature.

Hybrid. A composite laminate comprised of laminae or fibers of two or more composite material systems.

Hydraulic press. Press in which molding force is created by the pressure extended by a fluid.

Hydroclave. A pressure vessel that uses water as the pressure medium. A hydroclave can be pressurized to 3000 psi. The risk of explosion or fire is considerably less in a hydroclave.

Hydrophobic. Capable of repelling water.

Hydroscopic. Capable of absorbing and retaining atmospheric moisture.

Impregnate. In reinforced plastics, the saturation of the reinforcement with a resin.

Impregnated fabric. A fabric impregnated with a resin.

Inclusion. A physical and mechanical discontinuity occurring within a material or part, usually consisting of solid, encapsulated foreign material.

Insulator. Material which conducts minimal electric current or heat.

Integrally heated. Tooling which is self-heating through electrical heaters such as cal rods.

Interlaminar. Term pertaining to the area existing between two layers of a laminate.

Kevlar. Organic polymer composed of aromatic polyimides.

Knitted fabrics. Fabrics produced by interlooping chains of yarn.

Lamina. A unidirectional single ply or layer in a laminate.

Laminate. A term commonly used to identify a cured lay-up of laminae.

Lay-up. A stack of laminae placed in position in the mold; the process of placing reinforcing material in position in the mold. A description of the component materials of a laminate.

Mandrel. A fixture or male mold fused for the base in the production of a part by lay-up or filament winding.

Mat. A fibrous material consisting of randomly oriented chopped filaments or swirled filaments with a binder, available in blankets of various widths, weights, and lengths.

Mat binder. Resin applied to the fiber and cured during the manufacture of mat to hold the fibers in place and maintain the shape of the mat.

Matrix. The essentially homogeneous material (resin) in which the fiber system of a composite is embedded.

Moisture absorption. The pick-up of water vapor from air by a material. It relates only to vapor withdrawn from the air by a material and must be distinguished from water absorption, which is the gain in weight because of the take-up of water by immersion.

Mold. Cavity into which the resin/fiber composition is placed and from which it takes form to shape composite parts by heat and pressure.

Mold-release agent. a liquid, powder, or wax used to prevent sticking of molded articles in the cavity.

Mold surface. Side of laminate that faced the tool.

Molding. Shaping of a resin/fiber composition in or on a mold, usually under heat and pressure.

Molding cycle. Period of time for the complete sequence of operations to take place on a molding press.

Molding pressure. Pressure applied to the ram of an injection machine or press to force softened plastic to fill the mold cavities completely.

Monomer. A relatively simple compound which can react to form a polymer.

Nesting. Placing of plies of fabric so that yarns of one ply lie in the valleys between the yarns of the adjacent ply (nested cloth).

Nonwoven fabric. Material produced by compressing together yarns, fibers, or rovings, with or without a scrim carrier (see mat).

Nylon. Generic name for all synthetic polyimides.

Out-time. The time prepreg is exposed to ambient temperature, i.e., the total amount of time the prepreg is out of the freezer. The primary effects of out-time are to decrease the drape and tack of the prepreg while also allowing it to absorb moisture from the air.

Overcuring. The beginning of thermal decomposition because of too high a temperature or too long a molding time.

Oven dry. The condition of a material that has been heated under prescribed temperature until there is no further significant change in its mass. Usually refers to the removal of adsorbed moisture.

Overlay sheet. A nonwoven fibrous mat (in glass, synthetic fiber, etc.) used as the top layer in a cloth or mat lay-up to give a smoother finish or minimize the appearance of the fibrous pattern.

PAN fibers. Polyacrylonitrile fibers. The raw material for graphite fibers.

Parting agent. Lubricant or release agent used to coat a mold or cavity to prevent the molded piece from sticking to it.

Peel ply. Outside layer of laminate which is removed to achieve improved bonding or additional plies. The peel ply can be left on for greater protection during handling.

Peel strength. Adhesive bond strength, as in pounds per inch of width, tested by stress applied in a peeling mode.

pH. A measure of acidity or alkalinity of a solution with a value of 7 representing neutrality and increasing acidity corresponding to lower values and increasing alkalinity corresponding to higher values.

Pick. An individual filling yarn or roving in a fabric.

Pick count. The number of filling yarns per inch of woven fabric.

Pin holes. Small cavities in the surface of a cured part or holes in bag film.

Pitch fiber. Fibers derived from a special petroleum pitch.

Plasticizer. A material of lower molecular weight added to a polymer to separate the molecular chains.

Pleats. In placing the vacuum bag over the part, pleats in the bag provide extra material over the part to eliminate bridging to the laminate. Pleats are at least two to three inches in height, every two to three feet, as necessary, to allow room for unusual shapes or for protrusions in the lay-up without danger of puncturing the bag.

Polymer. An organic material composed of molecules characterized by the repetition of one or more types of monomeric units.

Polymerization. A chemical reaction in which the monomers are linked together to form a polymer.

Porosity. A condition of trapped pockets of air or gas within a solid material.

Positive mold. A mold designed to apply pressure to a piece being molded with no escape of material.

Postcure. Additional elevated temperature cure, usually without pressure to complete the cure. In certain resins, complete cure is attained only by exposing the cured resin to higher temperature after the original cure cycle.

Pot life. The length of time that a catalyzed resin system retains a viscosity low enough to be used in processing.

Precursor. Either the PAN or pitch fibers from which carbon and graphite fibers are derived.

Prefit. Method for checking the fit of mating parts before bonding.

Preimpregnation. See prepreg.

Prepreg. Ready-to-mold material in sheet form which may be cloth, mat, or paper impregnated with resin and stored for use. The resin is partially cured to a B stage and supplied to the fabricator who lays up the finished shape and completes the cure with heat and pressure.

Pressure. There are various kinds of pressure: dead weight, vacuum, super-heated steam, fluid water pressure, and compressed air. Dead-weight pressure is preferred for room temperature curing of parts. Vacuum pressure requires bagging to evacuate the air in a part. Vacuum produces 14.5 psi pressure. Super-heated steam pressure has become obsolete because of plumbing corrosion and the expense of replacing valves, pipes, etc. Fluid or water pressure (hydraulic pressure) is common in hydroclave operations. The main requirement is to have sufficient pressure on the part in all directions to obtain a void-free assembly.

Pressure bag molding. A process for molding reinforced plastics, in which a tailored flexible bag is placed over the contact lay-up in the mold, sealed, and clamped in place. Fluid pressure, usually compressed air, is placed against the bag, and the part is cured.

Reinforced plastic. A plastic with relatively high stiffness or very high-strength fibers imbedded in the composition.

Release agent. A material applied in a thin film to the surface of a mold to keep the resin from sticking to the mold.

Resin. Organic material which flows when subjected to stress. Most resins are polymers (see matrix).

Resin content. The amount of matrix present in a composite either by percent weight or percent volume.

Resin-starved area. Area of a composite part deficient in resin matrix and with excessive fiber content.

Rupture. Cleavage or break from physical stress due to applied load.

Sample. A small portion of a material or product intended to be representative of the whole.

Scrim. A low cost nonwoven open-weave reinforcing fabric made from continuous filament yarn in an open mesh.

Sealant. Material in paste or liquid form that hardens or cures in place forming a seal.

Selvage. Outer woven edge of a fabric parallel to the warp or length.

Shelf life. Length of time a material can be stored and retain all of its original characteristics.

Shrinkage. Relative change in dimension between the length measured on the tool when it is cold and the length measured 24 hours after it has been removed.

Solute. The dissolved material.

Specific gravity. the density or mass per unit volume of a material divided by the density of water.

Splice. Joining of two ends of glass fiber yarn or strands usually by means of an air-drying adhesive.

Spray-up. Techniques of using a spray gun as the processing tool. In reinforced plastics, fibrous glass and resin can be simultaneously deposited in a mold.

Staging. An intermediate stage of a thermosetting resin that is between monomer stage and complete cure.

Starved area. An area in a plastic part which has too little resin to wet out the reinforcement completely. This may be caused by improper wetting or excessive molding pressure.

Starved joint. An adhesive joint which does not have enough film thickness of adhesive due to insufficient adhesive spreading or because of excessive pressure during lamination.

Storage life. The period of time during which a liquid resin or packaged adhesive can be stored under specified temperature conditions and remain suitable for use. (Also called shelf life.)

Stress crack. External or internal crack caused by mechanical stresses.

Surfacing mat. A very thin mat, usually 3 to 5 mils thick, or highly filamentized fiber glass used to produce a smooth surface on a reinforced plastic laminate.

Tack. Degree of stickiness when referring to a resin prepreg material.

Tape. Unidirectional prepreg material.

Thermocouple (TC). Thermocouples are used to measure and record temperature differential in the part being cured. Thermocouple wires are usually placed in the flash or trim area. These wires can be iron constantine, type J or equivalent, and chrome alumel type K. The chrome alumel TC wires are usually used where the cure temperature is very high, such as 800°F+. Wires must not be bent or crimped as they will become inoperable.

Thermoplastic. A plastic material that is capable of being repeatedly softened by application of heat and repeatedly hardened by cooling.

Thermoset. Plastic material that changes, during cure, into an infusible and insoluble material.

Time. The interval between events, i.e., start and completion of a cure cycle.

Tow. Untwisted bundle of continuous filaments of fibers.

Tracer. A fiber added to a prepreg to verify fiber alignment.

Unbond. An area within a bonded interface between two adherends in which the intended bonding action failed to take place (see debond).

Unidirectional laminate. A laminate with nonwoven reinforcements and all layers laid up in the same direction.

Vacuum. A state of being sealed off from external/environmental influences, state of emptiness. A near-perfect vacuum is 14.5 psi or 29.5 Hg. Note: Two inches of mercury (Hg) is comparable to 1 psi pressure.

Vacuum bag molding. A process in which a sheet of flexible material plus a bleeder cloth and release film are placed over the lay-up, sealed at the edges of the mold, and a vacuum is applied between the bag and the lay-up. The entrapped air is removed by vacuum and the part is cured with temperature, pressure, and time. The part is bagged to remove excess air and volatiles and also to apply an even distribution of pressure during the cure cycle.

Vent cloth. Lay or layers of open-weave cloth to provide a path for vacuum to reach the area over a laminate being cured (see breather cloth).

Venting. In curing a part in an autoclave, turning off vacuum source and venting vacuum bag to the atmosphere.

Voids. Air or gas has been trapped and cured into a laminate or bond line.

Volatiles. Materials in a resin formulation that are driven off as vapor during cure cycle.

Warp. Yarn running lengthwise in a woven fabric (see fabric fill face).

Water absorption. Ratio of the weight of water absorbed by a material to the weight of the dry materials.

Weave. Particular manner in which the fabric is formed by interweaving yarns.

Wet lay-up. A method of making a reinforced product by applying the resin system as a liquid while the reinforcement is put into place.

Whisker. A short single crystal fiber or filament. Whisker diameters range from 1 to 25 microns, with aspect ratios between 100 and 15,000.

Working life. The period of time during which a liquid resin or adhesive, after mixing with catalyst, solvent, or other compounding ingredients, remains workable (also see pot life).

Wrinkle. A surface imperfection in laminated plastics in one or more outer sheets of paper, fabric, or other base which has been pressed in or out.

X-axis. In composite laminates, an axis in the plane of the laminate which is used as the zero degree reference for designating the angle of a lamina.

Yarn. A generic term for strands or bundles of continuous filaments or fibers usually twisted and suitable for making textile fabric.

Yarn, plied. Yarns made by collecting two or more single yarns together. Normally the yarns are twisted together, though sometime they are collected without twist.

Zero bleed. A laminate fabrication procedure that does not allow loss of resin during cure. (Also called net resin systems.)